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A Predictive Model to Optimize the Collection of Data Needed to Characterize Fluvial Sand Bodies

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WES

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Prepared for Headquarters, U.S. Army Corps of Engineers

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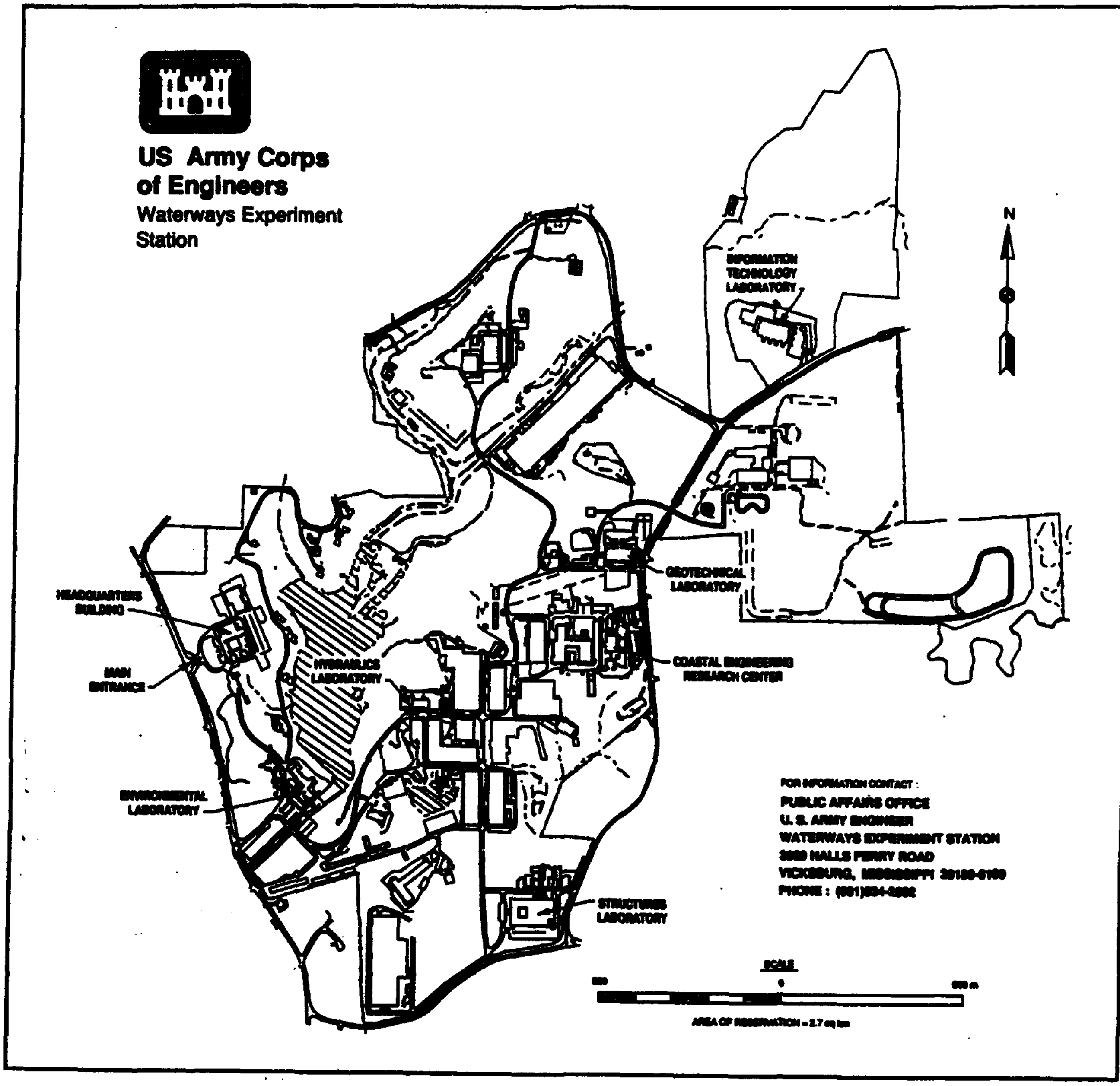

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Preface

This report is based on a dissertation submitted by D. W. Schmitz in partial fulfillment of the Ph. D. degree at Texas A&M University. The dissertation was completed May 1991. The text of this report is the product of Dr. D. W. Schmitz, now at Mississippi State University. The idea for the study reported herein was contributed by Dr. J. R. May of the Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station (WES). Dr. May also provided portions of the data used in the study and provided financial support through WES. The report was prepared for publication in 1992-1993. Direct supervision was provided by Mr. J. L. Gatz, Chief, Hydrogeology and Site Characterization Section. General supervision was provided by Dr. A. G. Franklin, Chief, Earthquake and Engineering Geology Division, and Dr. W. F. Marcuson III, Director, Geotechnical Laboratory.

Acknowledgment is made to Dr. Schmitz's committee which consisted of Drs. C. C. Mathewson, P. A. Domenico, R. R. Berg, K. W. Brown, and J. E. Russell for their guidance during the study and preparation of the dissertation, upon which this report is based.

Appreciation is also extended to Dr. P. F. Hadala, Messrs. E. V. Edris, R. L. Larson, and J. B. Warriner of the Geotechnical Laboratory, and Dr. T. A. Wittig of the Department of Mathematics and Statistics, Mississippi State University for their advice and comments.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.876	square meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
miles (U.S. statute)	1.609347	kilometers
square feet	0.09290304	square meters
square miles	2.589998	square kilometers

1 Introduction

Purpose

The presence of contaminants in the near surface ground water has resulted in numerous geotechnical and ground water related studies. Most of these studies have focused on some particular area of interest, such as the delineation of a particular plume or the geotechnical characterization of a specific site for waste disposal.

The amount of data required for characterizing any such site is driven by a general unwillingness to accept any degree of risk and a lack of understanding of the subsurface. Both result from being unable to directly "see" below the surface.

Obtaining the required data, such as from borings or monitor wells, at a contaminated site is hazardous and costly. Other factors which must be considered beyond the normal costs associated with site investigations are, the cost of protective clothing and protective equipment needed for workers, the potential exposure to the workers of hazardous material during the investigation, and the risk of further environmental contamination.

To obtain the necessary subsurface data, the site is usually sampled on a grid pattern. This occurs because most ground water studies are conducted on the premise that the aquifers are homogeneous and isotropic. For regional ground water studies to determine yield from an aquifer, these assumptions can usually be used satisfactorily. However, at small sites, variability in the aquifer is critical for contaminant movement. Here the geometry of the more permeable materials is a major factor in the flow of contaminants in ground water.

For example, if a discontinuous sand body is discovered at a site, additional data collection is initiated to define the extent of that sand body. This is commonly done with more grid style sampling, on a closer spacing and this "regridding" may go through several iterations, until data points which sufficiently define the discontinuous sand body, are established.

A grid pattern does not consider the geology of a site, and results in excessive data points, many of which do not add pertinent information. This excessive data collection increases the risk of exposure, as well as the expense of

the operation. A 27 square mile[1] area at Rocky Mountain Arsenal, Colorado has about 3,400 soil borings and 1,600 monitoring wells for the purpose of site characterization for hazardous waste cleanup (Duplancic and Buckle 1989). Had an information based, rather than grid based, boring plan been followed some of these might not have been necessary.

Many urban areas throughout the world are built on sites adjacent to streams and rivers. Thus, the industrial developments associated with these areas are located on fluvial deposits, which contain discontinuous sand bodies. Therefore, a need exists to bring geology into the site investigation process in order to limit the number of data points needed to properly characterize discontinuous fluvial sand bodies.

A model predicting a minimum number of data points necessary to characterize discontinuous sands, such as those commonly found in fluvial settings, could reduce the number of data locations needed and thus the risk of the hazards and costs of drilling at contaminated sites.

Paleogeomorphic features, such as discontinuous fluvial sand bodies, are important in controlling the movement of ground water. Detailed geomorphic and statistical analysis of discontinuous sand bodies can predict the type of sand body. If the sand body is penetrated by one or more borings, and the width of the sand body can be estimated, the correct data point spacing can be determined. Once the shape and orientation of a particular sand body has been determined, the appropriate hydrologic or physical control can be implemented.

From the above ideas, a predictive model was developed. The model was designed primarily for characterization of sites with geotechnical and ground water applications, however, it could also be adapted to other uses. For example, in oil and gas exploration, it could be used for following a discontinuous sand reservoir. It could also be used for following a discontinuous sand body for pursuit of reduction-oxidation fronts where mobile metals such as uranium may have been precipitated. Other uses for which the model could be adapted are certainly possible.

Scope of Research

This study was conducted to develop a predictive model for locating sample points needed to characterize discontinuous fluvial sand bodies, and thus, minimize data needed to define the sand body, minimize the exposure to hazards and to reduce the expense and time spent obtaining such data. This was accomplished by:

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[1] A table of factors for converting SI (metric) units of measurements to non SI units is presented page ix.

a. developing a rationale for exploration,

b. selecting sites for testing the exploration rationale,

c. selecting and applying statistical techniques to determine locations of future sample points,

d. establishing confidence of data point locations from established geology, and

e. developing a predictive model.

The following methodology was used to develop the model to determine the optimum number and location of data points needed to adequately characterize discontinuous sand bodies.

A rationale for exploration was developed using minimum requirements for the number of data points needed, taking into consideration the probability of encountering a discontinuous sand body and the site boundary.

A systematic evaluation was conducted to determine how the hazard and expense of obtaining data for characterizing a discontinuous sand body at a contaminated site could be reduced. Figure 1 shows the results of a comparison of the typical method of gridding (part A) with a systematic approach (part B). The systematic approach places data points around the perimeter of a site and defines a discontinuous sand body by predicting its location from stratigraphic data, rather than just gridding and regridding the entire site. It was evident that bringing geology into the data location selection portion of site investigations as soon as possible would reduce the number of data points needed.

To conduct the systematic evaluation, how the optimal data should be collected to reduce the hazard must be determined. To determine how the optimal data is collected, the control of the scale on the optimal data collection was determined. This is shown in Figure 1, part B, as follows:

a. The control of the scale was determined by the variability of the site. To establish the variability of the site, the environment of deposition was determined.

b. The environment of deposition was determined by interpretation of stratigraphic information, such as sedimentary structure, mean grain size, and relative percentages of quartz and matrix material (Berg 1986).

c. Once the environment of deposition was determined, the morphology was predicted, which dictated the scale of the data collection.

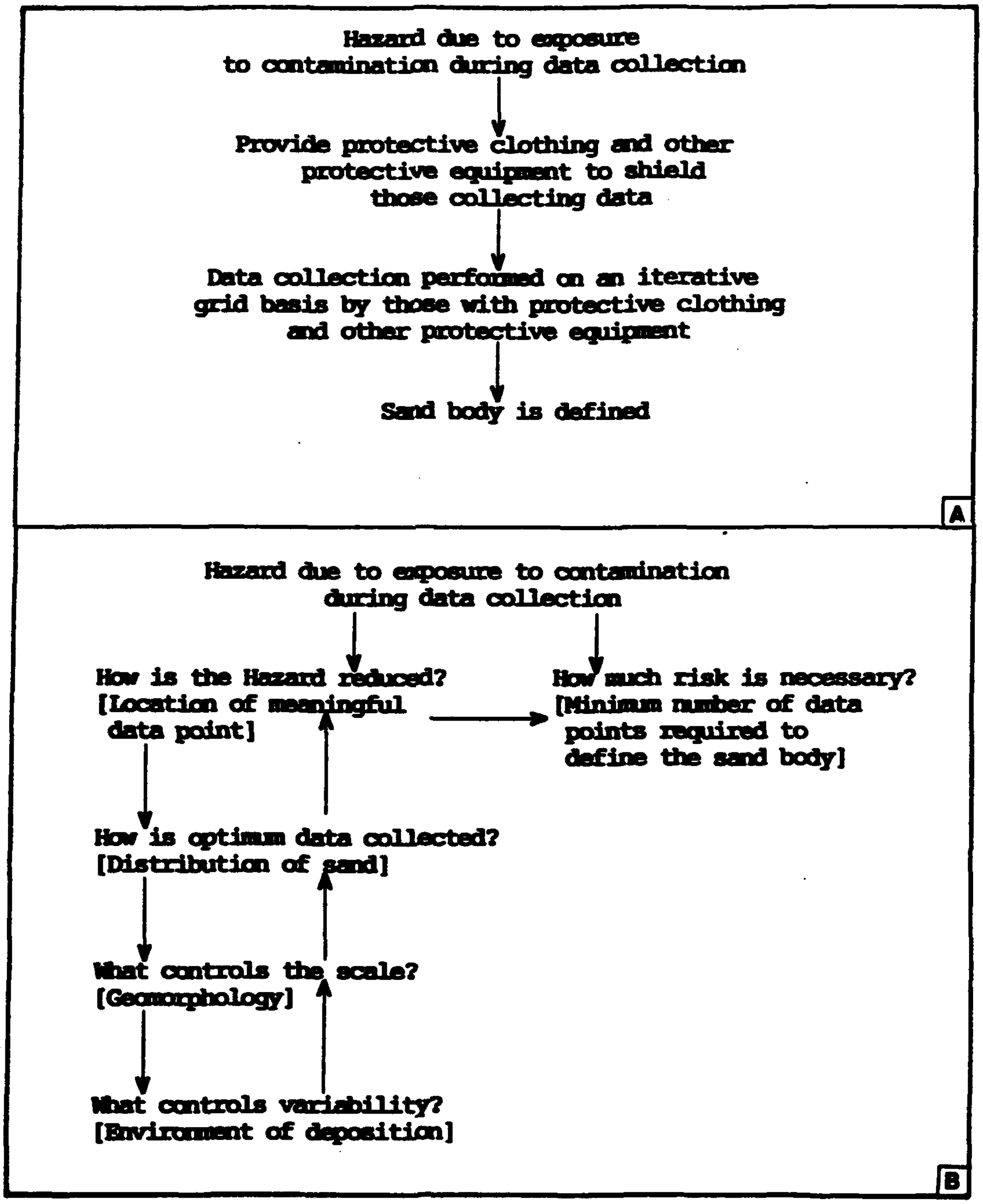

Figure 1. Diagrammatic representation of (A) the typical method of defining a discontinuous sand body and (B) a systematic approach of defining a discontinuous sand body

d. With the scale of the data collection established, the distribution of the sand was determined, using Lorenz and others (1985) method for a meander belt sand. The distribution of the sand controls the probability of establishing a meaningful data point.

e. The probability of obtaining a meaningful data point controls the exposure to the hazards and the expense of obtaining the data points.

This rationale was tested in study areas, selected from a literature survey and established criteria met by the sites. The sites contained a specific geologic condition (a discontinuous sand body) and a data base which had an abundance of data already available. The data base itself was defined to determine the amount and type of data available and its density (which controlled the resolution of interpretations).

Such a site allowed for:

a. The extent of the site's discontinuous sand body to be established, such as from isopact and sand distribution maps.

b. Comparison of predicted parameters with that which is actually present. This, in turn, allowed for a specific degree of confidence for various data point spacing to be determined.

Statistical techniques were selected which could be applied to determine the probability of the location of a data point being meaningful and the degree of confidence of that location.

Kriging was the geostatistical technique chosen, based on numerous authors' descriptions of the applicability of kriging to geologic data sets (Clark 1979, Davis 1986, Di 1989, and many others). Kriging interpolates irregularly spaced data to a regular grid, which was used for contour plotting.

Kriging compared pairs of known data points to generate a curve, called a variogram. The variogram shows the variation of the numeric variable versus distance from control points. Kriging estimates the value of a variable away from control points. These estimates are produced in a grid, which can be contoured to provide a map of the estimated variable values. Additional information on Kriging is contained in Appendix A: Kriging Tutorial.

Once the sand body morphology was estimated from stratigraphic methods, sand body width and probability of dual penetration were used as the pairs of known data points to generate different data point spacing. This allowed for a specific data point spacing to be established, based on the probability desired, for reencountering the sand body.

Also, sand thickness was contoured and confidence intervals determined for the sand thickness. With abundant data, the number of data points was varied. Sand thickness and confidence was determined for each variation,

resulting in a minimum amount of data sufficient to define the sand body. This minimum data being based on the confidence desired.

The rationale for exploration, stratigraphic methods for predicting extent, and statistical methods for predicting data point locations and confidence for those locations were combined into a predictive model.

Related Studies

Previous studies have been concerned with either, (1) the methods for interpretation and prediction of environments of deposition (Berg 1986, 1970; Ethridge et al. 1975 and LeBlanc 1972) or, (2) statistical predictive methods (David 1977, Davis 1986 and Mousset-Jones 1980).

May (1985) dealt specifically with the application of kriging techniques in conjunction with paleogeomorphic predictive techniques delineating the overall trend of a fluvial sand sequence and delineating areas where additional data were needed.

Di and others (1989) used geostatistics in designing sampling strategies for soil surveys. Their study determined the utility of geostatistics in assisting design of a sampling scheme for soil morphological properties in an alluvial system. Kriging was also used in the study for predicting soil property values at unsampled locations.

McBratney and Webster (1983) also applied kriging to regional soil sampling and suggested that the actual efficiency achieved in their studies was three - to nine - times greater than that estimated by the classical statistical methods. However, few other studies of this kind have been made to substantiate the claim (Di et al. 1989).

2 Rationale for Exploration

Sampling Strategy

The first step, as in any geological investigation is a literature survey. A literature survey should give at least an idea of the geology at a particular site and thus, whether or not a fluvial sand deposit is expected. Literature may or may not give information as to any expected trend (i.e., dip) of "bedrock" on which fluvial deposits may have developed and thus the expected trend of any potential fluvial deposits. In some areas the published information may be detailed enough to show that there are indeed fluvial sand bodies expected in the specific horizon (formation) of interest. There are, however, areas for which no information at all is published, so that the first information would be from the site of interest itself. This could be from surface morphology as in the case of surface or very near surface interest, or from actual sampling as in the case of below surface interest.

This model will be based on the premise that little detail is known at the site of interest itself. The only information that may be known is that there is the possibility of a fluvial sand body at the site.

In nearly any site investigation there will be boundaries within which the investigation will be restricted, at least initially. In contaminated or characterization sites, for example, the boundary will usually be the property boundary of the project itself, at least initially. For oil and gas or mineral exploration, the boundary will be the lease block.

For any site investigation there will be lines bounding the area of interest. To encounter a fluvial sand body that may enter or exit the site, the boundary should be the first region in which to obtain data. The spacing of the data collection locations will be based on the legal requirements and/or the smallest size sand body that is important in the project, or which can be predicted. The spacing requirements can range from about one hundred feet to thousands of feet. More discussion about the predicted size limitations will come in later sections.

In the case of contamination and characterization sites, the order in which the boundary is drilled can be dictated by logistics, since a minimum number of data points may be required, regardless of the geology. If, however, there

is some variation possible, due to the geology encountered or if literature indicates an expected trend, a specific approach is more desirable.

There are two possible cases: (1) the sand body is at or near the surface, and (2) the sand body is below the surface. In either case, surface geophysics is a tool which may be brought into use. In the case of near surface contamination and characterization sites, resistivity, electromagnetic, or ground penetrating radar may be used, running lines along the boundaries itself. For sites suspected of having deeper sand bodies seismic lines may be run along the boundaries.

Each of these surface geophysical methods have drawbacks which may cause them to be of little or no use. These drawbacks include: cultural interference, which inhibit the use of resistivity and electromagnetic surveys; and layers of different characteristics, which mask anything below them, preventing ground penetrating radar or seismic from "seeing" the horizon of interest.

Since boundaries of many sites correspond with roadways, fences, utilities, etc., the utilization of surface geophysics for these sites is often severely limited. Masking and resolution needed for deeper zones limits use of surface geophysics in the case of many fluvial sand bodies.

If little or no geophysical information is available or obtainable, then the locations for data, such as from drilling, are needed in an order to optimize encountering a fluvial sand body.

The dip of the bedrock in the zone of interest generally will dictate the orientation. Such information may have been gathered from the literature. For a site with no information available, a minimum of three drill holes to define the general stratigraphy under a site would be placed, and a three point problem solved to obtain the dip of the bedrock for the horizon in question. These three stratigraphic locations should be placed along boundaries, so that they can provide other data of interest for the site.

Once the dip of the bedrock in question is obtained, the placement of data locations can be optimized for encountering a fluvial sand body. The application for which the model is used will dictate the actual locations. For example if a north - south trend is expected in the fluvial sand body (where the drainage control is only due to a southward dipping bedrock) in a contaminated or characterization site, the southern most boundaries would be drilled first. The southern boundary would be the expected direction for a sand body to exit the site, due to stream flow, assuming the dip of the bedrock is or was the control for any stream developed upon the bedrock. This would also be the direction for any contaminant or potential contaminant migration off site, based on expected ground water flow in such a sand body.

Once the first (south in the example) boundary is drilled, the drilling program should work from this first boundary on both sides (to the north along the east and west boundaries in the example). These would be the next most

likely boundaries for an exiting fluvial sand deposit, based on the bedrock trend.

Finally, the remaining boundaries (north in the example) would be drilled in the event that a fluvial deposit may extend through it. A sand body may not occur at an expected boundary for various reasons. One reason is that the sand body may not be continuous through the site. Another reason is that a stream may have developed under different controls than bedrock dip, or perhaps the bedrock dip was different at the time the stream developed than it is today.

The boundary drilling should be carried to completion, regardless of whether or not a fluvial sand body has been encountered early in the boundary drilling, because more than one may exist at a site.

If no fluvial sand is found in the boundary exploration, drilling should progress inward in the same manner as the boundary was drilled, because a fluvial sand body may exist within the site, but not extend out of it. This could be caused by a facies change, or a fault where a sand body would have been displaced. This is important in contamination or characterization investigation as a collection or potential collection area within the site for contamination.

Environmental Interpretations

Once a sand has been encountered at a site, the stratigraphic information must be interpreted to establish the environment of deposition, whether or not it is a fluvial sand, and whether or not it is from a meandering stream. This is done by analyzing sedimentary structure, texture, and composition (Visher 1965).

Of these sources, the sedimentary structures are of most importance, because they reflect the processes that caused the sediment's distribution. This is followed in order of importance by textural change and composition. Other knowledge which can be helpful in interpretation include regional stratigraphic setting, nature of adjacent sediments, types of associated fossils, and lateral variations in the sandstone (Berg 1986). Information can also be obtained secondarily from geophysical log responses, and porosity and permeability. From a vertical sequence through the sediments in the horizon of interest, the general morphology can be predicted. Figure 2 shows common sequences of sedimentary structure, texture, and composition from sandstones of different depositional environments. A sandstone could be determined to be of fluvial origin if: (1) the sequence of sedimentary structures range from dune (representing high flow regime) at the base to ripples (representing low flow regime) at the top; (2) grain size decreases upward; and (3) composition is mostly quartz with some matrix, the matrix increasing near the top of the sequence.

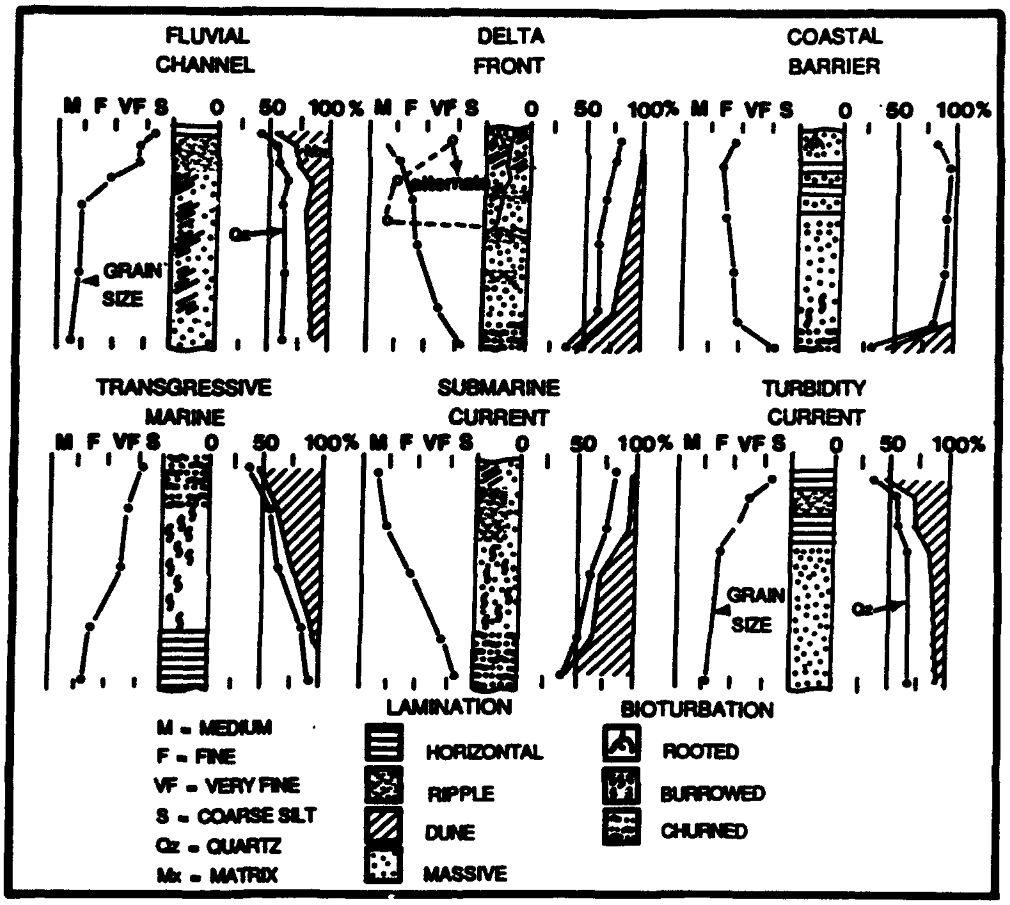

Figure 2. Common sequences of sedimentary structure, texture, and composition of sandstones of different depositional environments (after Berg 1986)

There are, however, two types of fluvial deposits: braided and meandering. Sand bodies deposited from braided streams have a lower sinuosity (the ratio of channel length to valley length) than the meandering sand body deposits. Braided channels have a sinuosity of less than 1.5 and meandering channel's sinuosities are equal to or greater than 1.5 (Leopold and Miller 1964). Unfortunately, the depositional sequence remains the same regardless of the curvature, since the sequence is based on the flow regimes. But, braided sandstone bodies average on the order of 2000 ft in width while the meandering sand bodies have much wider distribution, on the order of 10,000 ft or more (Berg 1986). An exception to this is a meandering stream carrying a large suspended load, resulting in small point bars because of sand-poor sediment. From one vertical sequence, the type of stream (i.e. braided vs. meandering) may not be obtained. If the vertical sequence is thick (thickness vs. width relationships will be discussed in the next section) the sand body could be assumed to be meandering.

The morphologies of sand bodies that are not modern are based on those observed in modern-day environments of deposition. Each environment of deposition has a characteristic distribution of sediment (LeBlanc 1972).

Morphology Estimation

Once determined (or assumed) to be from a meandering stream, the width of the sand body can be estimated by using meander belt amplitude to approximate the sand body width. Meander belt amplitude is calculated from channel widths. The channel widths are calculated from channel depths. The channel depths being equivalent to sand thickness (Lorenz et al. 1985). This can be done from one data location by making certain assumptions. However, in estimating the width of the sand body, some assumptions must also be made initially. A primary assumption is that meander belt amplitude approximates sand body width (Lorenz et al. 1985). Another necessary assumption is that sinuosities are greater than 1.7 (ratio of length of channel to down valley distance). This is necessary because with less than a 1.7 sinuosity there is little relationship between width and depth (Leeder 1973). Successive sweeps of a migrating channel will erode tops of previously deposited sands, resulting in incomplete thicknesses, however it must be assumed that a mature meander belt is isolated within the floodplain deposits and that the thickness observed represents that of the maximum thickness.

The sand body is assumed to be deposited as point bars, the thickness of which is an approximation of the depth of the channel (Allen 1965). This is shown in Figure 3, Part A. If the sand body is sandstone, rather than unconsolidated sand, the thickness measured must be corrected for compaction from sand to sandstone. Ethridge and Schumm (1978) suggest a 10 percent factor as reasonable for this compaction factor.

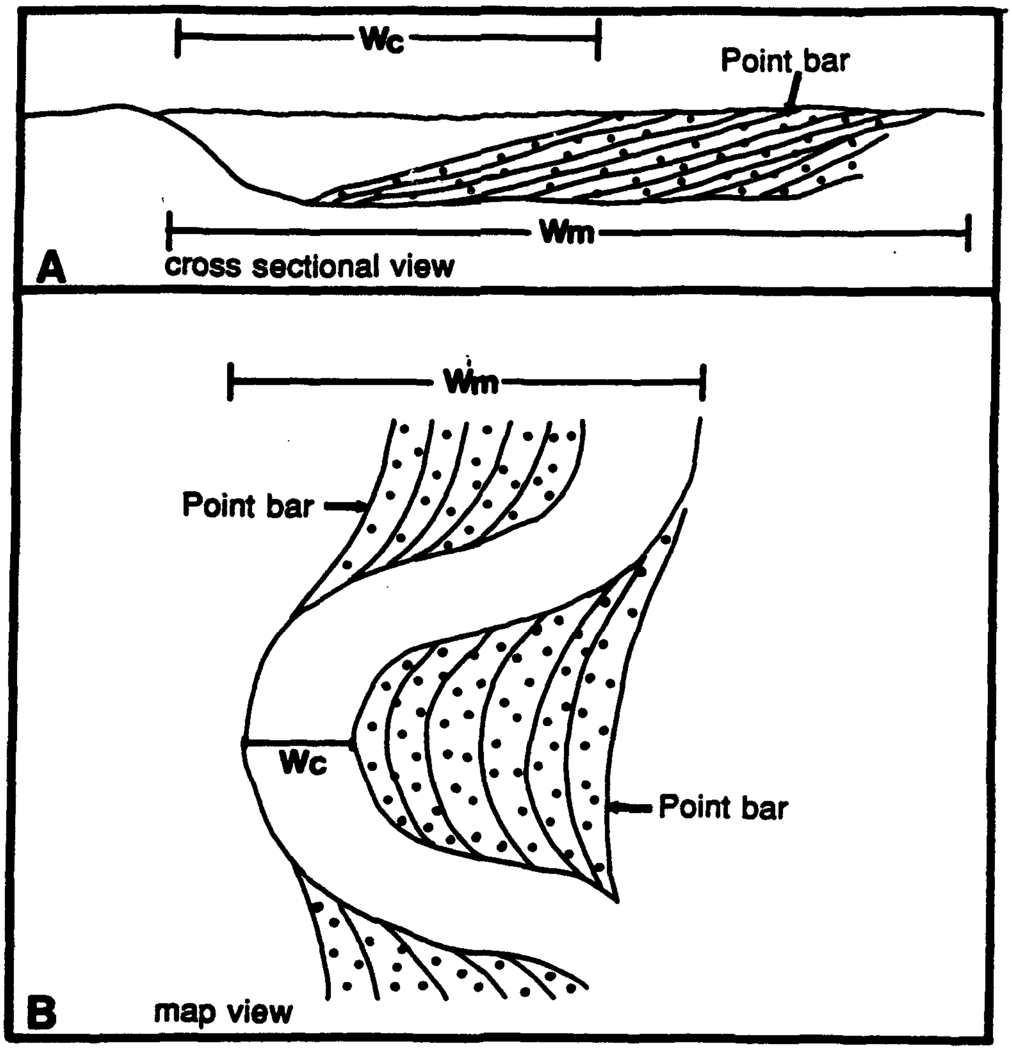

Figure 3. Relationships between point bars, channel width, and meander belt amplitude (after Lorenz et al. 1985). Wc is stream channel width; Wm is meander belt width.

Once the depth is obtained, Leeder's (1973) formula

$$W_c = 6.8h^{1.54}$$

where

W_c = channel width, m

h = channel depth, m

yields channel widths. This formula is in meters, so any measurements in english units must be converted to metric units before using the formula.

Once the width is calculated, meander belt amplitude is obtained from Lorenz and others' (1985) equation

$$W_m = 7.44W_c^{1.01}$$

where

W_m = meander belt amplitude, ft

W_c = channel width, ft

The meander belt amplitude being the approximation of the sand body width. This is shown in Figure 3, Part B. This equation is for english units, so the metric width obtained from Leeder's equation must be converted to english units before being used.

Lorenz and others (1985) used both Leopold and Wolman's (1960) and Carlston's (1965) data to establish the relationship between meander belt width and channel width. These data contained a range of meander belt widths of approximately 10 ft, from physical models, to near 15,000 ft, from natural streams.

The estimated sand body width will be an average for sand body populations over the sedimentary section, and are subject to normal geologic variability, such as differences in thicknesses due to location within the stream channel or facies changes due to different periods of deposition. The original channel depths are assumed in this model and the original data set relating that depth to channel and meander belt width contain variabilities also. The model, however, produces satisfactory sand body width estimates.

Prediction of Additional Data Point Locations

Once the width of the sand body has been estimated and the location of one point in the sand body is known, the spacing of another data point location is established based on the probability of encountering the sand body again. Data point locations in the sand body and outside the sand body are necessary to define the boundary of the sand body.

Two theorems of elementary statistics are necessary for derivation of the probability that a second data location encounters a sand body if one has already encountered it. The two theorems are: the law of compound probability and the law of total probability.

The law of compound probability is that the probability of two events (say A and B) occurring, P(AB), is equal to the product of the probability of one event occurring (say P(B)), and the conditional probability of the other event (A) occurring given that the first has already occurred, or $P(AB) = P(B)P(A \mid B)$.

The law of total probability states that if there are two mutually exclusive events, (say C and D) then the probability of either occurring ($P(C \cup D)$) equals the sum of the probability of each occurring, or $P(C \cup D) = P(C) + P(D)$.

Using these probability statements, Lorenz and others (1985) developed the probability function for dual penetration of a sand body, assuming an ideal case, as depicted in Figure 4. In this case, the meander belt sand body is infinitely long, has a width of W_m, and the data location spacing is w. The probability of both data points intersecting the sand body if one data location point is a distance x from the center of the sand body is Θ/π, where Θ, in radians, is defined on Figure 4 and is a function of x. So, $P(A \mid B) = \Theta/\pi$, where A is a dual intersection and B is a data point intersection a distance x from the center of the sand body. The probability of a data point location being within the distance of from $x + dx/2$ to $x - dx/2$ from center of the sand body is $2dx/W_m$ (dx is the mathematical notation for the differential, where x is the variable of integration). So, $P(B) = 2dx/W_m$. Symmetry about the center of the sand body results in the factor of 2.

From the law of compound probability, the probability of both occurring is $P(AB) = P(B)P(A \mid B) = 2\Theta dx/(\pi W_m)$. It does not matter where the data points intersect the sand body, as long as there is dual intersection.

If a data point intersects the sand body at a different distance than in event B, (say event C) then the law of total probability gives the probability as $P(AB \cup AC) = P(AB) + P(AC)$.

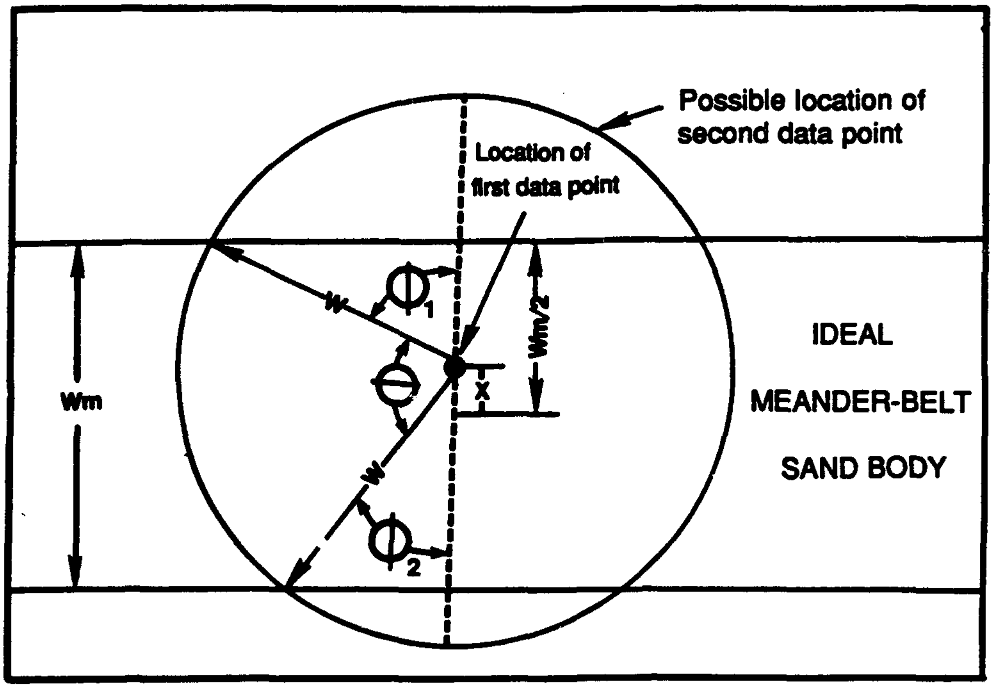

Figure 4. **Ideal case for dual penetration of a sand body (after Lorenz et al. 1985)**

Being extending to all possible distances

$$P(Dual\ Intersection) = (2/\pi W_m)) \int_{O}^{Wm/2} (\theta dx)$$

Since

$$\theta = \pi - \varnothing_1 - \varnothing_2$$

where

$$\varnothing_1 = \begin{cases} \cos^{-1} ([W_m/2 - x]/w) & if\ x \geq W_m/2 - w \\ 0 & if\ x < W_m/2 - w \end{cases}$$

$$\varnothing_2 = \begin{cases} \cos^{-1} ([W_m/2 + x]/w) & if\ x \leq w - W_m/2 \\ 0 & if\ x > w - W_m/2 \end{cases}$$

then

$$\text{P(Dual Intersection)} = (2/\pi W_m) \int_0^{Wm/2} (\pi - \phi_1 - \phi_2) dx$$

Using these probability relationships, probability of dual penetration vs. sand body width can be plotted for various data point location spacing. From the resulting curves, probability for dual intersection can be obtained for any combination of sand body width (as estimated) and data point location spacing. Figure 5 shows probability of dual penetration vs. sand body width for several data point location spacings. A computer program, MathCAD, was used to calculate the probabilities for the curves shown in Figure 5. MathCAD is a computational software copyrighted (1986-1989) by Mathsoft, Inc., Cambridge, Massachusetts. The results of the calculations are contained in Appendix B. The program was verified by comparison of its computed values with those, for the same variables, computed by May (1985) and by Lorenz and others (1985). Both May's and Lorenz and others' curves are contained in Appendix C.

Entering the plot of sand body width vs. probability with a high probability produces a data point spacing likely to intersect the sand body again. Conversely, using a low probability value produces a data point not likely to

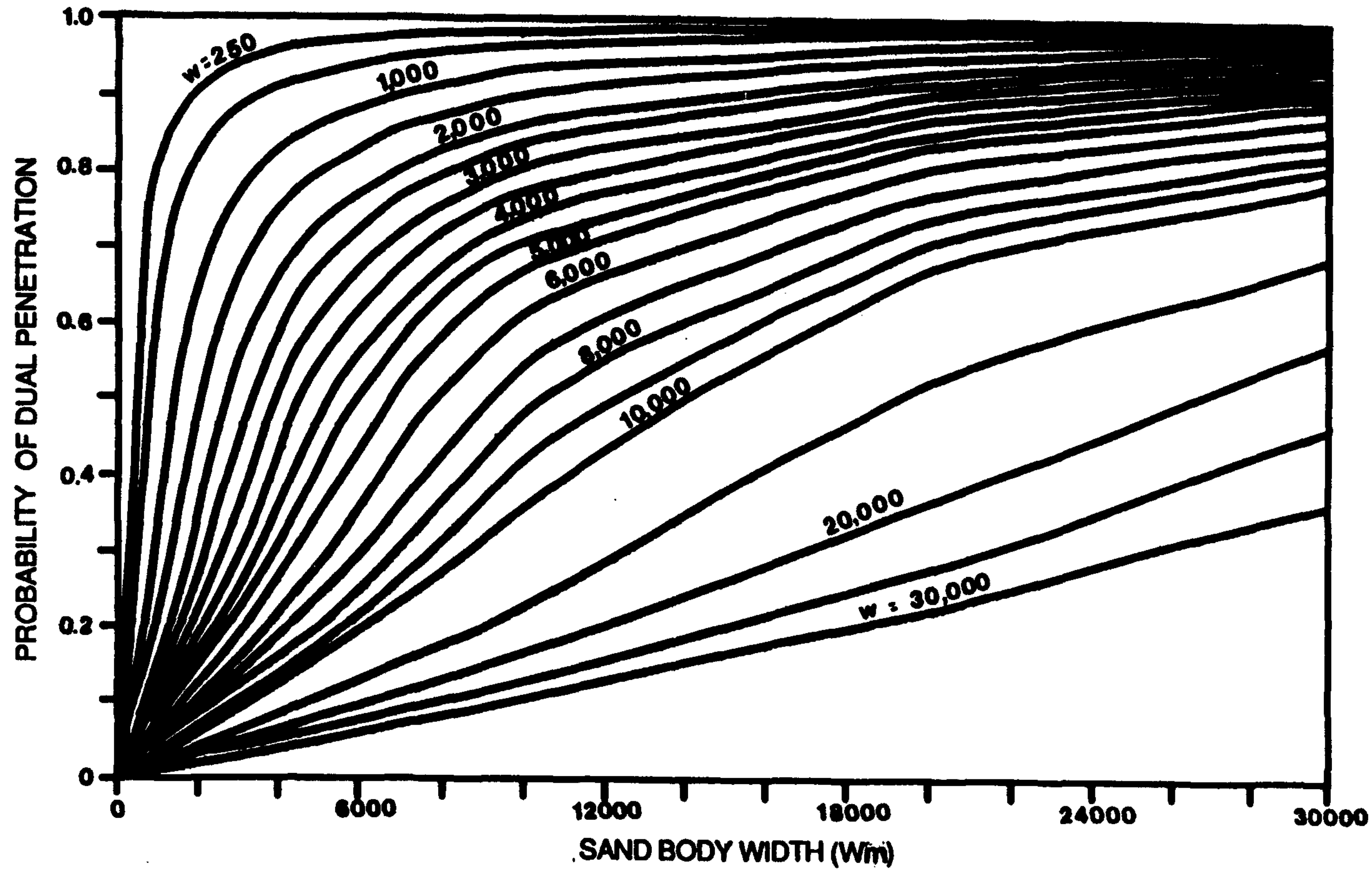

Figure 5. Plot of sand body width (W_m) vs. probability for selected data point location spacing (w)

intersect the sand body. In proceeding radially from the first intersection point, it is necessary to use appropriate probabilities and resulting radii to both intersect and not intersect the sand body. In this manner, the sand body boundary location is delineated.

The spacing for location of the additional data point, in any case, takes the form of the radius of a circle, the center of which is the data point location which previously intersected the sand body. This is shown in Figure 6. In the case of boundary drilling, there would not be a full circle for the location of the additional data point due to the portion of the circle falling outside of the boundary line.

The location of the data point itself on the circle (or portion of) can be arbitrary. However, it should be placed in a manner as to lend itself, as easily as possible, to the locating method used. Certainly, accessibility will play an important role in the actual placement of the data point location.

If, or when, more than one data point location is to be placed on the circle, the distance between the successive data points should be the same as the radius of the circle, thus keeping the same spacing. As new data are added, the spacing can of course be adjusted as necessary, based on new calculations.

Once sufficient data are obtained, such as from boundary borings, kriging, as described in the Introduction section, can be used to help select the location on the circle for data location spacing, which will give a high probability of being a useful location. Kriging is a geostatistical technique that can be used to estimate irregularly spaced data, such as drilling information, to a regular grid which can be used for contour plotting, such as that of a geologic surface. The kriging variance shows the areas where additional data are needed. An area shown with most error and overlapping the circle would be the area to place the next data point.

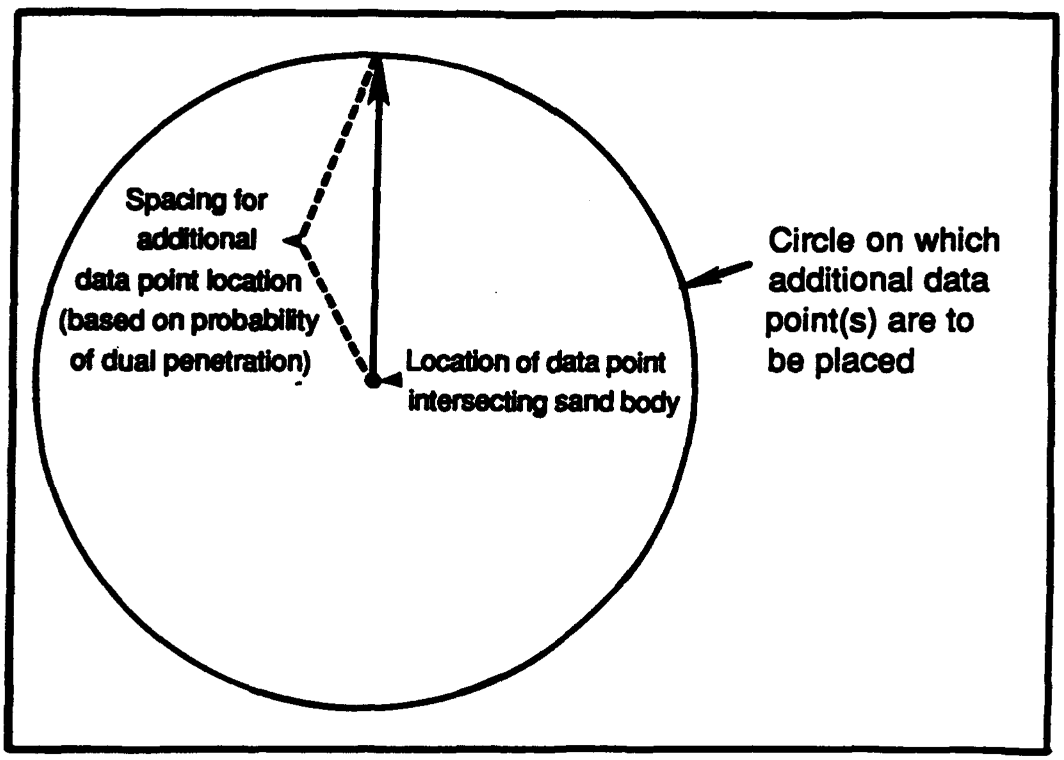

Figure 6. Additional data point location spacing based on probability of dual penetration

3 Case Study

To test the rationale for exploration described in the previous section, a site was chosen which was known to have a discontinuous sand body and which had a large amount of data already collected and available. Thus, the site would lend itself conveniently to the application of this rationale.

The site chosen was a part of the Rocky Mountain Arsenal near Denver, Colorado. Figure 7 shows the general location. The Arsenal is located northeast of Denver, Colorado, adjoining the northern portion of the Denver Stapleton International Airport. Figure 8 shows the Arsenal and its vicinity. The application of the rationale for exploration was limited to a four square mile portion of the Arsenal because of the availability of usable data in that particular area and due to the location of the particular sand body chosen for this application. This four square mile area is shown in Figure 9. It is composed of Sections 1 and 2, Township 3 South, Range 7 West and Sections 35 and 36, Township 2 South, Range 7 West.

Due to contamination being detected in the groundwater below the Arsenal, numerous studies have been conducted to delineate the route(s) of migration (May 1985). This has resulted in a large quantity of geological data.

Geological data includes geotechnical reports, geophysical logs, boring logs, and core samples. This data was in sufficient quantity and of a quality that was useable in a hypothetical drilling program.

Several discontinuous sands have been delineated from the data. One of these sands was chosen as the sand to "target" during the application.

Geologic Setting

Rocky Mountain Arsenal is located in the Denver basin, a structural depression occupying a large area of Northeastern Colorado, Southeastern Wyoming and Western Nebraska. Within the basin the Lower Cretaceous and Tertiary rocks occupy an area of 670 square miles, from Greeley in the north to Colorado Springs in the south and from the Rocky Mountain front range in the west to near Limon in the east (Robson and Romero 1981). The location of the Arsenal within the basin is shown in Figure 10. The basin is filled

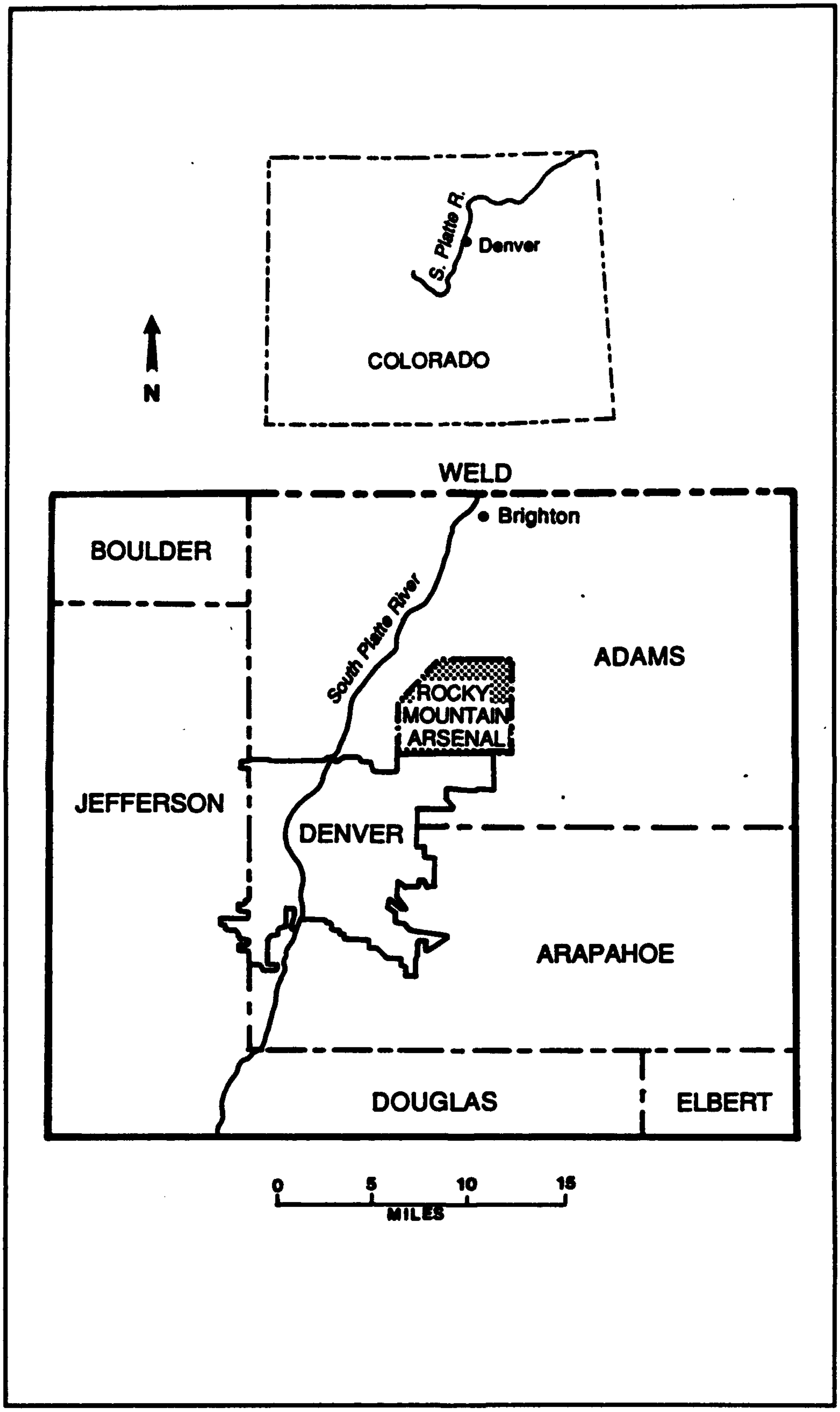

Figure 7. General location of the Rocky Mountain Arsenal (after Warner 1979)

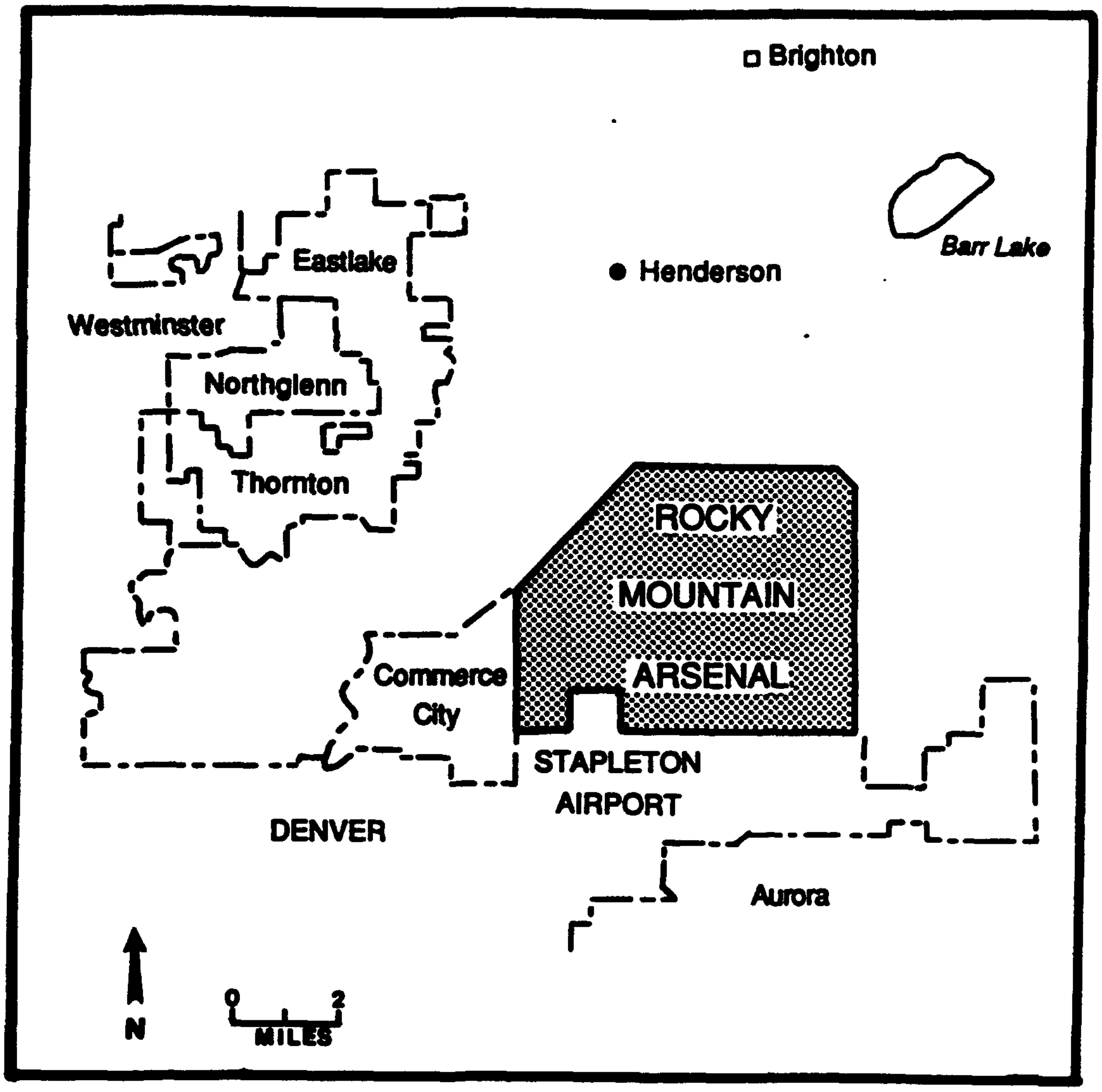

Figure 8. Rocky Mountain Arsenal and vicinity (from May et al. 1983)

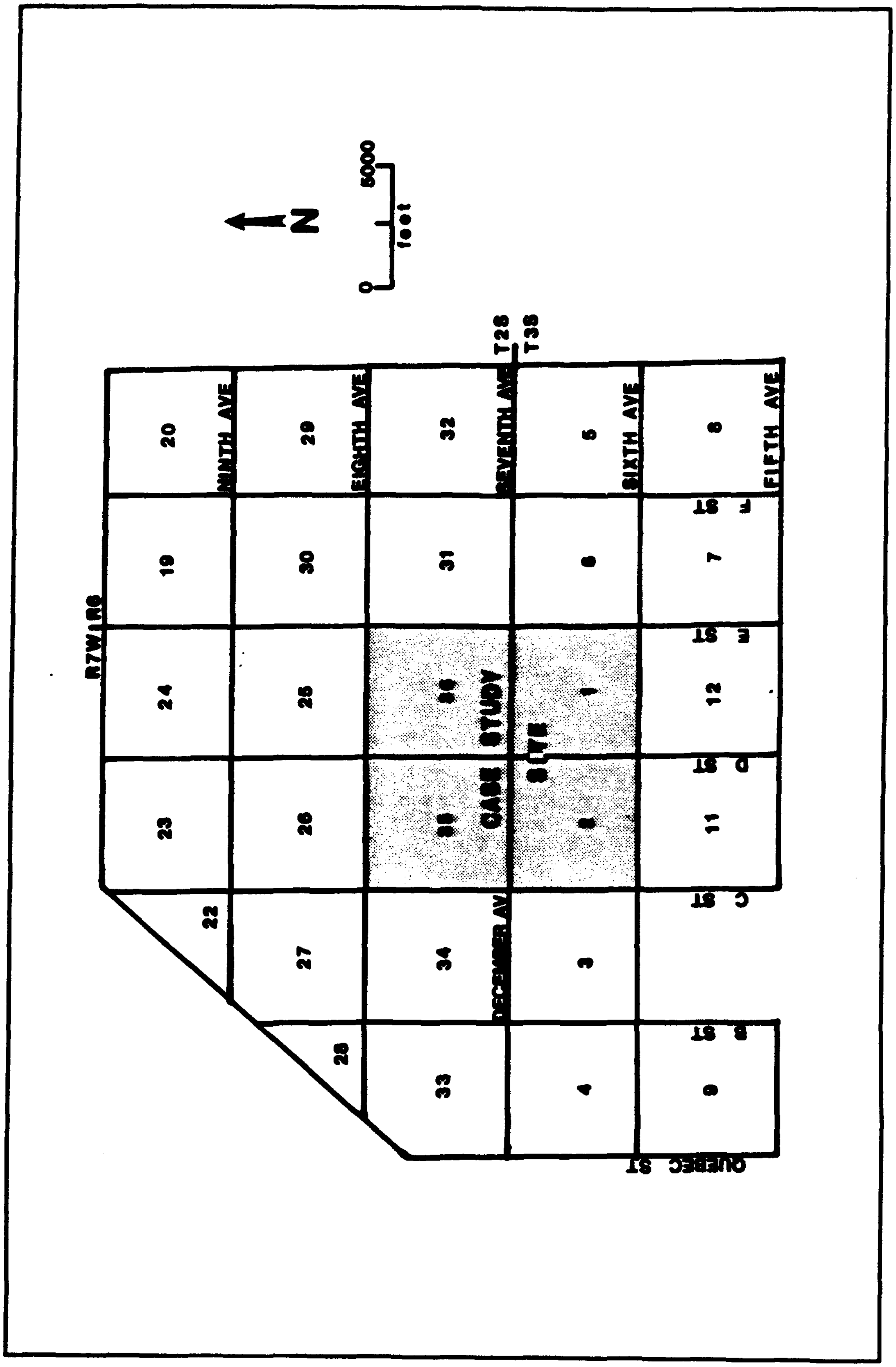

Figure 9. Case study area

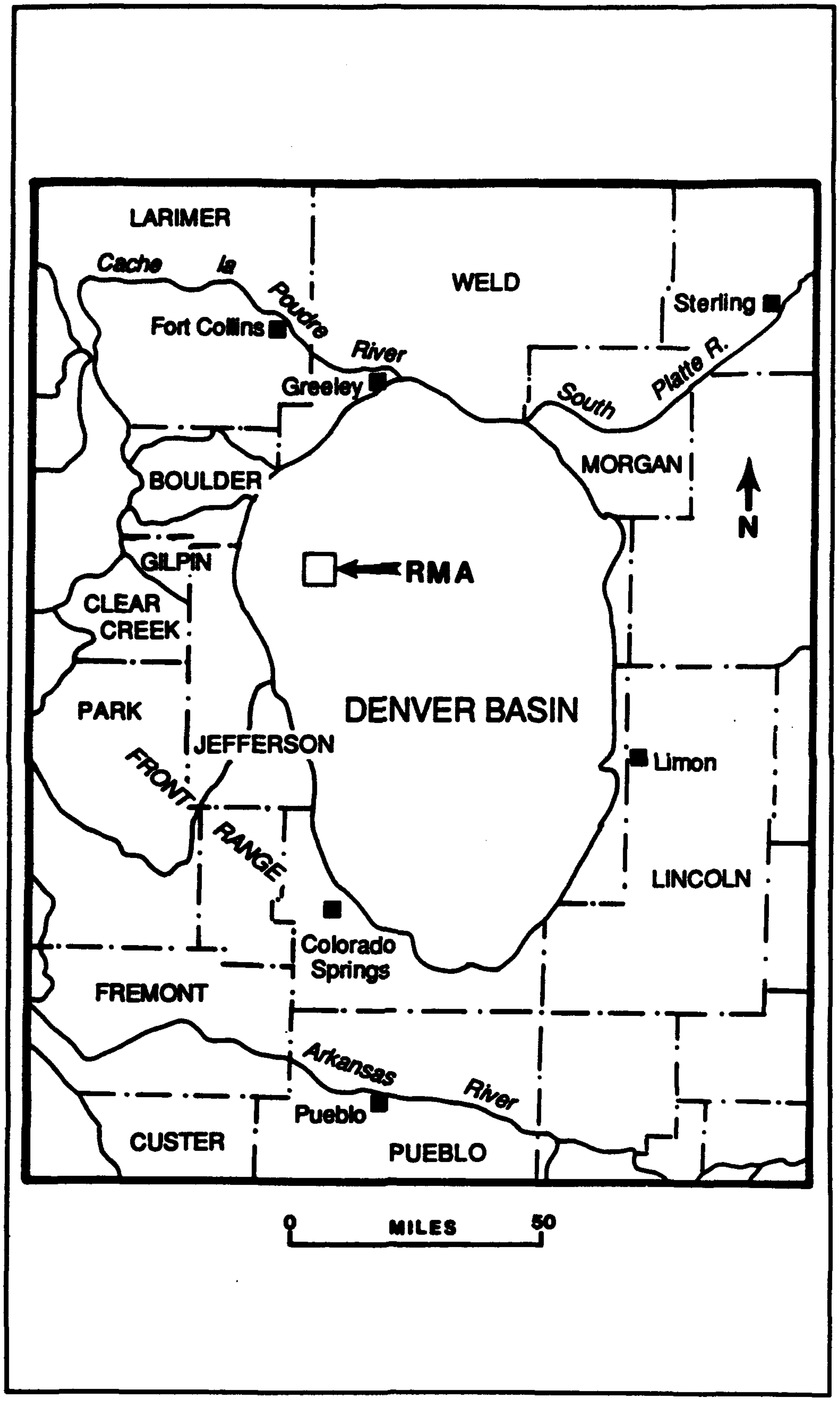

Figure 10. Rocky Mountain Arsenal in relation to the Denver basin (after Robson and Romero 1981)

with approximately 15,000 ft of sediments composed of limestones, sandstones, shales and conglomerates (Robson and Romero 1981).

The stratigraphic position of the Arsenal within the Denver basin is shown in Figure 11. At the Arsenal, the geologic formations of concern, with respect to this application, are the Late Cretaceous and Early Tertiary Denver formation and the Tertiary and Quaternary alluvium.

May (1985) states that the Denver formation is composed of 250 to 400 ft of interbedded clay shale, claystone, siltstone, sand, and sandstone. Low-grade coal, lignite, and carbonaceous clay shale are also present. The predominant olive-gray, brown, and green-gray colors in the formation are caused by rock fragments derived from the erosion of basaltic and andesitic lavas. The lowest elevations for the base of the Denver formation in the entire Denver basin are found along the eastern side of the city of Denver, including the southern portions of the Arsenal. The sands in the Denver formation are generally weakly cemented sandstones or compact fine- to medium-grained sands. Many of these sandy units represent deltaic channel deposits which grade laterally and vertically into silts and clay shales. The individual sand or sandstone layers are commonly lens-shaped and range in thickness from several inches to as much as 60 ft.

May (1985) describes the surficial deposits as having been deposited primarily by ancient streams. In some areas, a veneer of aeolian deposits occur, but for discussion purposes, these are included as alluvium. The surficial alluvial deposits are of Pleistocene and Recent age. Pre-Wisconsin deposits contain alluvial silts, sands and gravels. The Wisconsin-age alluvium was deposited as glacial outwash from the Rocky Mountain front range. The aeolian deposits were derived from glacial outwash. The deposits immediately overlying the Denver formation are identified as the Verdos alluvium of Kansan age. The Verdos is composed of boulders, cobbles, pebbles, and sands derived from granites and pegmatites and Cretaceous shale. The Verdos is up to 100 ft thick in the Arsenal area. Recent alluvial sand deposits have accumulated from several separate periods of deposition. Figure 12 shows the typical geology below the Arsenal.

From the several sand bodies that incised the Denver formation in the subsurface, the highest, thickest, and best delineated one was chosen as the "target" for application of the rationale for exploration.

Application of Rationale for Exploration

The location of the sand body chosen as the "target sand" dictated the area within the Rocky Mountain Arsenal for the application of the rationale for exploration. Figure 13 shows the location of this sand body within the Arsenal. The quantity of usable data dictated the actual boundaries for this application. Figure 9 shows the selected site boundaries.

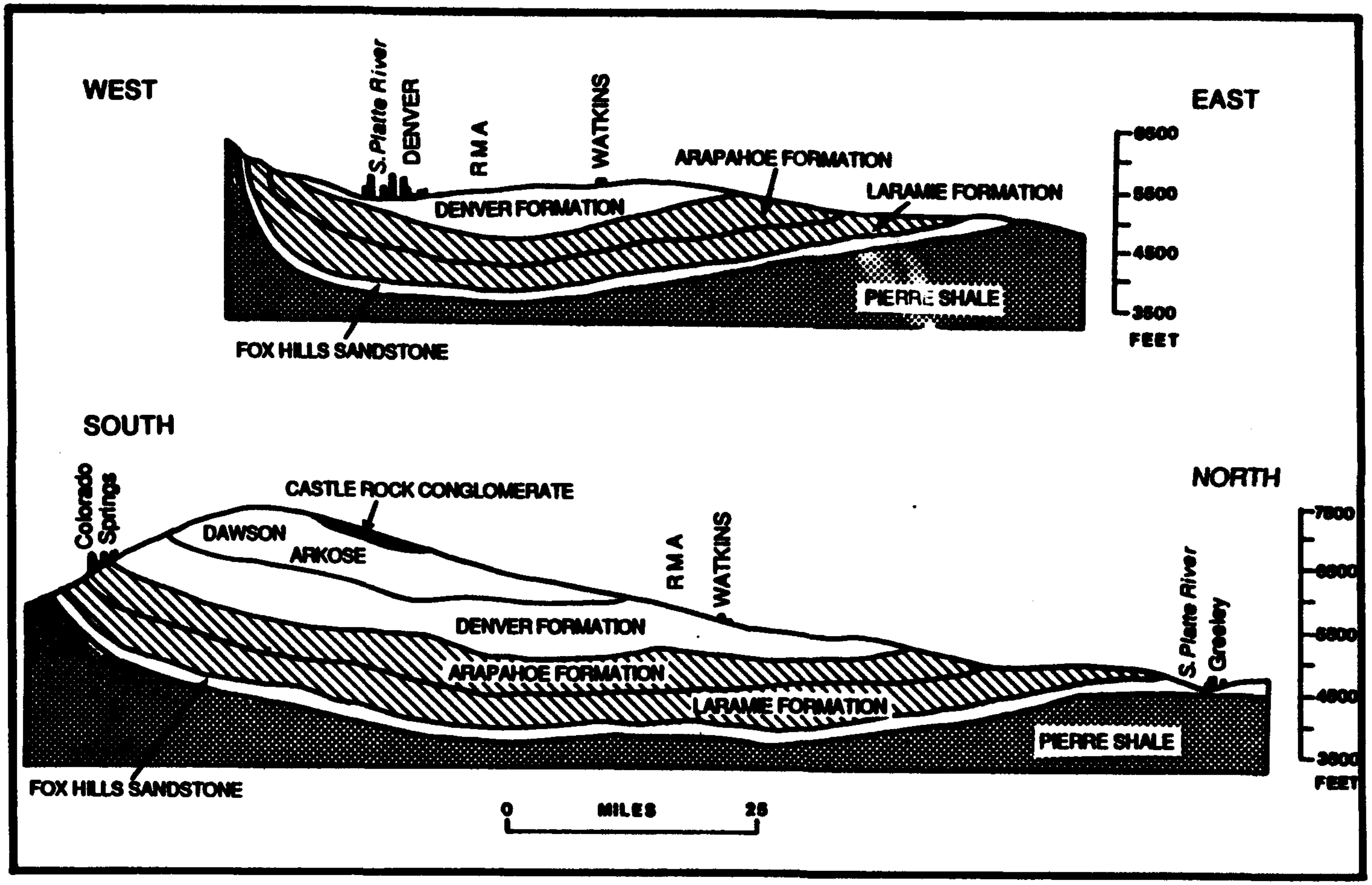

Figure 11. Stratigraphic position of the Rocky Mountain Arsenal within the Denver basin (after Robson and Romero 1981)

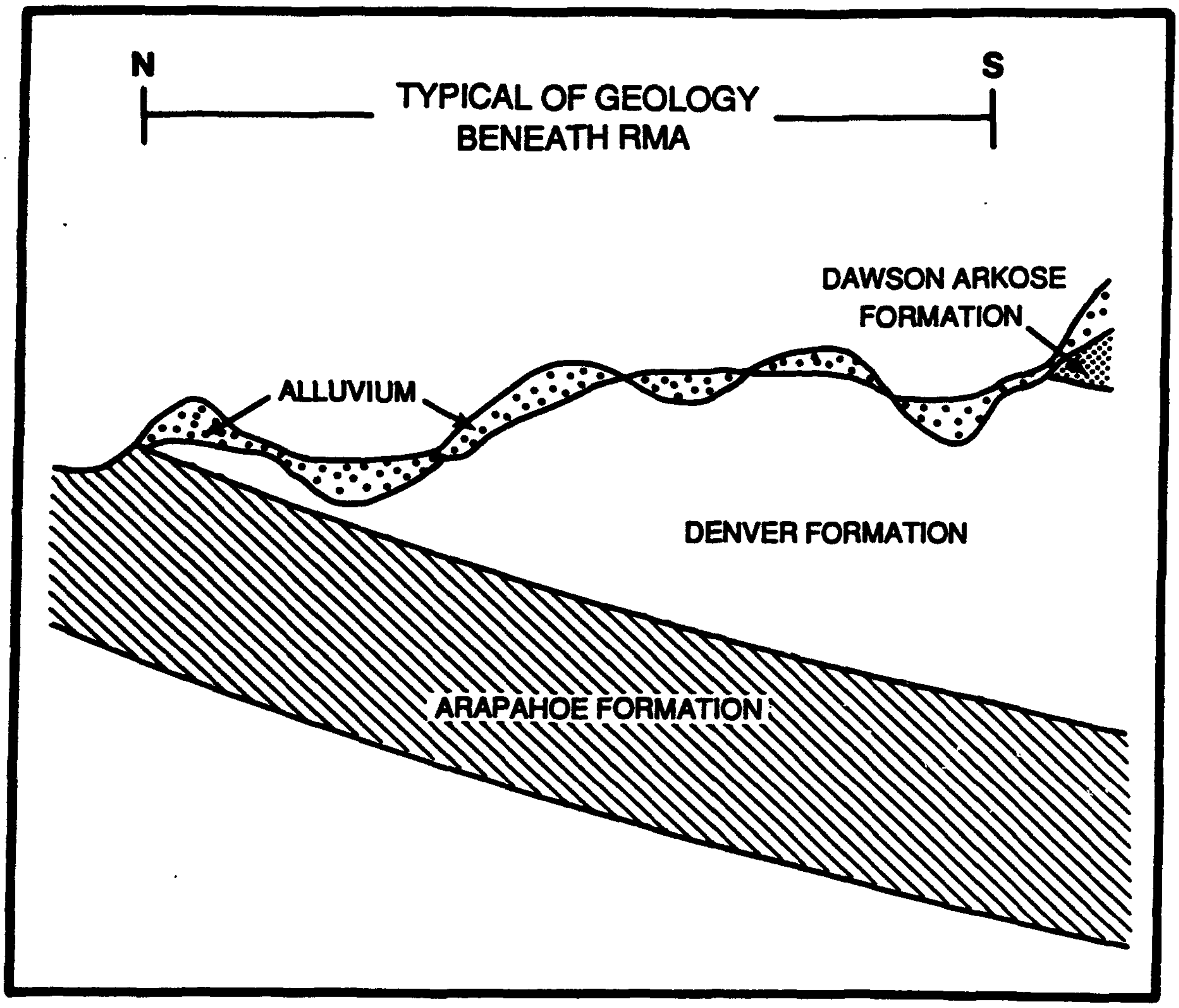

Figure 12. Typical geology below the Rocky Mountain Arsenal (after Robson and Romero 198^)

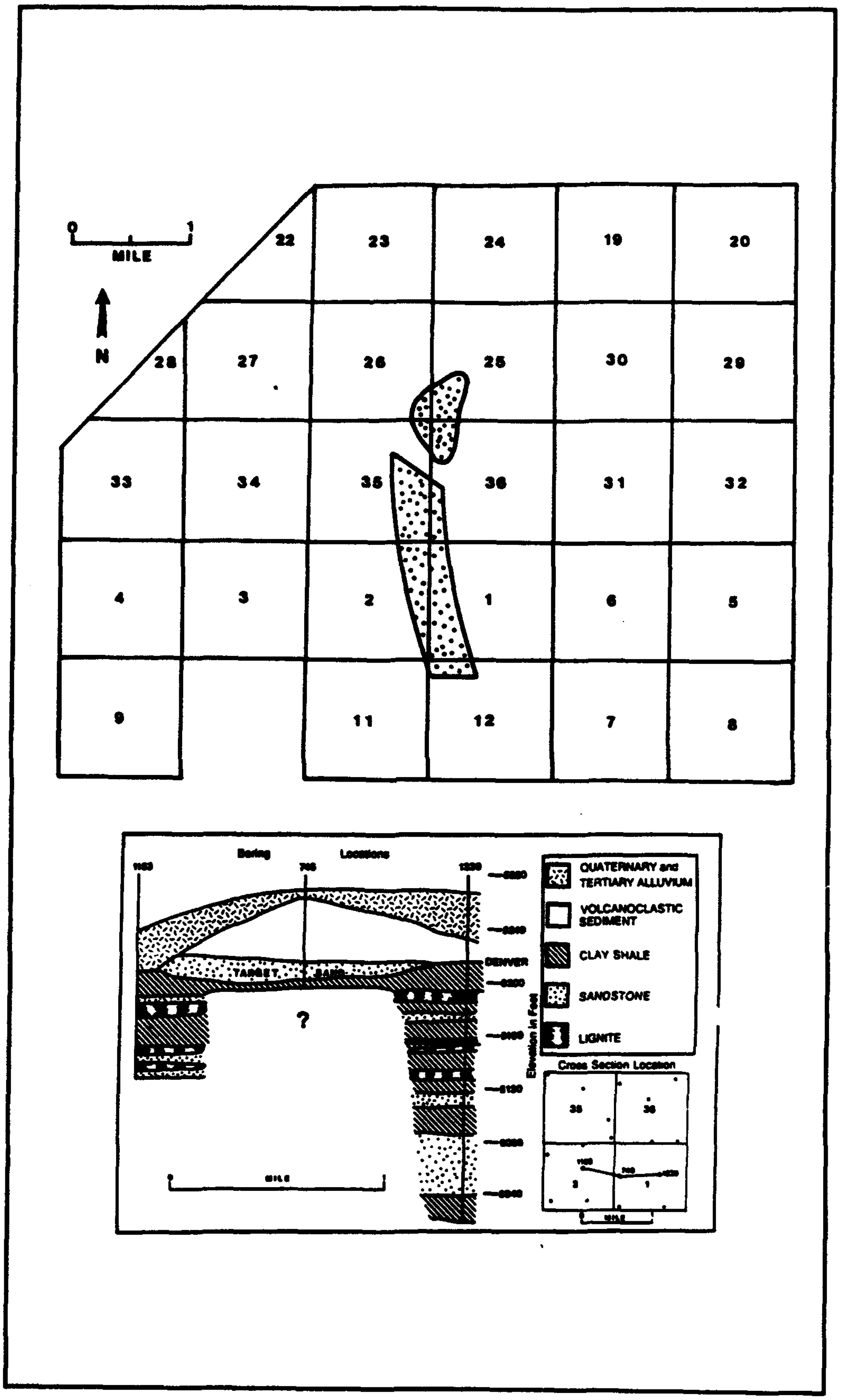

Figure 13. Location of the "target" sand body within the Rocky Mountain Arsenal (after May 1985)

With the site selected, the rationale for exploration described in the previous chapter was used for a hypotheoretical drilling exploration program.

Since a substantial amount is known about the geology and discontinuous sand bodies at the Arsenal, it was presumed that only the regional geology was known. From the regional geology a possibility existed for a sand body to be incised into the Denver formation.

An assumption was also made that there is too much cultural interference at the Arsenal to use surface geophysics to investigate the boundary of the site. Indurated sands and gravels in the area mask geophysical signatures at depth.

Since the regional geology shows the top of the Denver formation dipping to the south, the southern boundary of the site was hypothetically drilled first. A spacing of one mile was arbitrarily chosen for the boundary drilling spacing, although this could be initial spacing for a site investigation based on an expected sand body width or logistically based on Sections of the Public Land Survey. A Section is a square mile, and this land location system is present at the Rocky Mountain Arsenal. Existing borings located as close to this mile spacing as possible, were chosen to represent the hypothetical drilling locations. As in the case for these locations, as well as others that follow, the borings chosen had to have usable information, and thus were often not in the exact chosen location. This is acceptable, since logistics in actual drilling programs often dictate offsetting actual borings from desired locations. This offsetting can be due to inaccessibility which is due to rugged or swampy terrain, to buildings and other structures, or buried utilities.

The target sand was not encountered in any of the southern boundary borings. Next, borings to complete the western and eastern boundaries were chosen. Again, the target sand was not encountered. Then the boring to complete the northern boundary was chosen. This boring did encounter the target sand. Table 1 contains the location, boring number, and "target" sand thickness for the borings chosen in the hypothetical boundary drilling and subsequent borings. Figure 14 shows the locations of the boundary drilling borings. These borings are located with the Colorado state grid coordinates.

Using the data available from the boring (1228) which encountered the target sand, the environment of deposition was determined for that sand. The data available included grain size analysis, x-ray diffraction analysis, geophysical log, and detailed core description.

Sands generally occur in regular predictable sequences, that are characterized by vertical changes in composition, texture, and sedimentary structures. These ordered sequences contain information that provides keys to their method of transportation and deposition. By studying properties such as sedimentary structure, mean grain size, and relative percentages of quartz and matrix material, a sandstone can be categorized as to its environment of deposition (Berg 1986). This methodology was used to determine the environment of deposition of the sand body encountered between thirteen and thirty

Table 1
Rocky Mountain Arsenal Hypothetical Exploration Boring Locations and Sand Thicknesses in Sequence of Hypothetical Borings

Section	Grid Coordinate Location, ft East	Grid Coordinate Location, ft North	Boring Number	Other Number	Target Sand Thickness, ft
2	2,178,931	175,779	1124	SP13	0
1	2,183,891	175,445	1155	SP15	0
1	2,187,216	175,608	1143	SP16	0
36	2,188,139	180,921	1160	SP02	0
36	2,188,353	185,171	1188	E01	0
2	2,178,446	179,361	1123	SP08	0
35	2,178,426	185,575	1185	N06	0
36	2,183,794	185,108	1228	AP01	19.0
35	2,181,155	184,639	653	--	0
35	2,183,065	182,320	757	--	10.5
36	2,186,014	184,035	758	--	0
35	2,183,045	180,900	1251	AP25	28.6
1	2,184,234	177,874	746	--	10.4
2	2,181,060	178,469	1153	SP09	0
36	2,186,235	180,686	756	--	0
2	2,181,205	180,372	1247	AP21	0
2	2,181,444	176,282	1148	SP12	0
1	2,186,789	178,332	1239	AP12	0

two feet depth in boring 1228. The various procedures that were used are summarized in the following paragraphs. More details on these procedures are given in the Stratigraphic Interpretations section.

Detailed descriptions of the core from boring 1228 were generated during a previous study. These descriptions provided information on the lithology of the sand body.

In addition to sieve grain-size analysis, grain-size data was statistically analyzed to determine standard deviation and the relative degree of sorting of the grains by using grain size distribution curves. The degree of sorting was helpful in confirming the history of the sand.

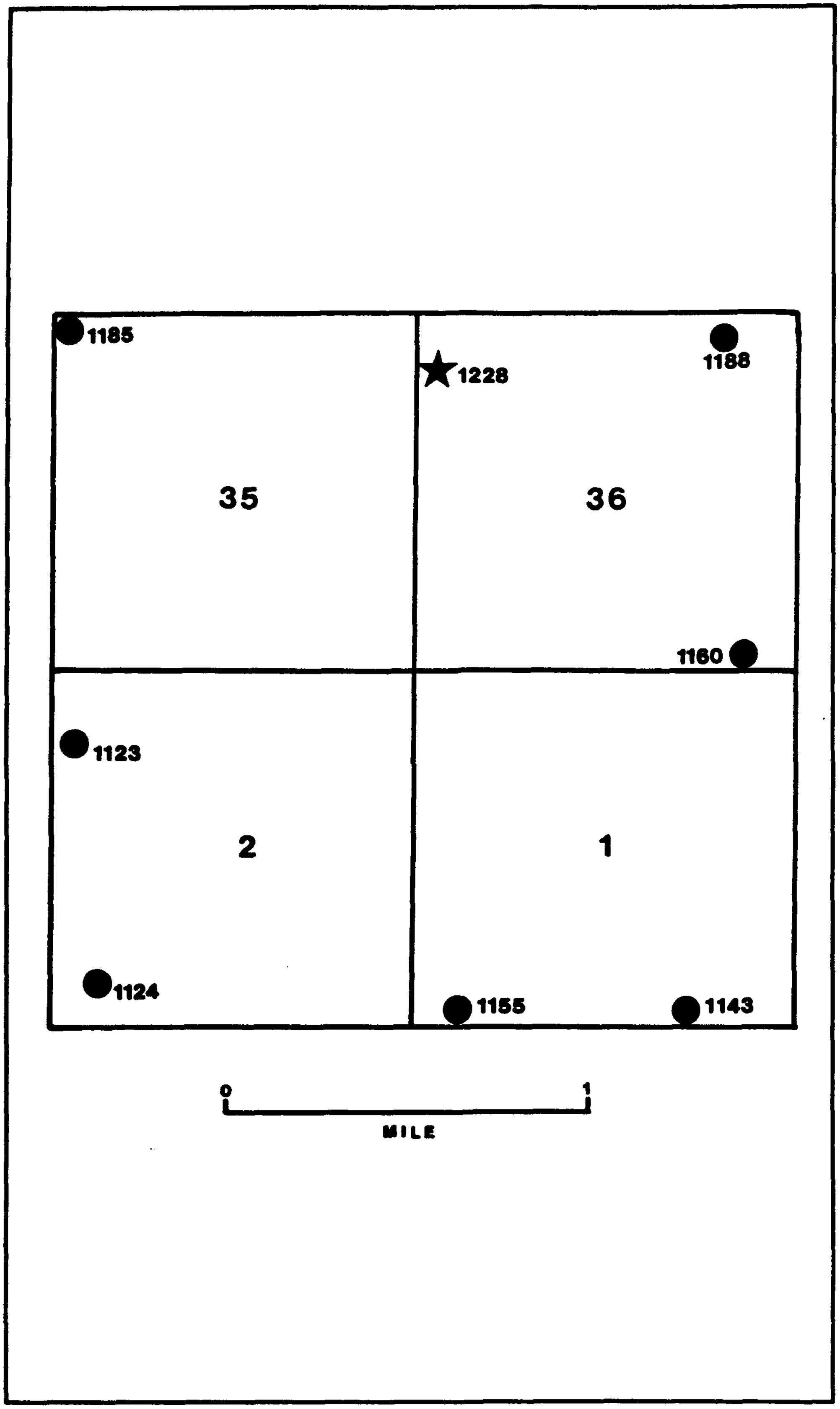

Figure 14. Drilling locations for the Rocky Mountain Arsenal site boundary

The geophysical log for boring 1228 was used to aid in establishing the abrupt lower contact of the sand body with the underlying Denver formation. The clay shale of the Denver formation is easily recognizable.

Selected samples were tested by x-ray diffraction to determine the percent of quartz present. The percentage of quartz is used in the indication of the environment of deposition. Mostly quartz with a little clay matrix, which increases upward, is typical for a fluvial sequence.

From this boring information, which is summarized in Figure 15, the environment of deposition was interpreted by comparison with diagnostic characteristics for a fluvial sand, which are shown in Figure 2.

The coal seam in boring 1228, at a depth of about 50 ft, was deposited in a swampy environment. The coal seam was overlain by a layer of olive-brown clay shale containing abundant organic material and sandy silt lenses. The clay shale which contains volcanic ash and worm borings was deposited in a low energy environment such as a shallow lake. A fine to medium grained non-cohesive to slightly cohesive alluvial sand was deposited over the clay shale. The abrupt lower contact of the sand with the underlying clay shale indicates that a stream deposited the sand, cutting down into the clay shale. The upper finer portions of the fluvial sand sequence was removed by a much younger stream which deposited gravel, sand, silt and clay on top of the Denver alluvial sand sequence.

With the environment of deposition determined to be that of.a meandering stream, the sand body width was estimated. Channel width was calculated from the sand thickness of 19.0 ft. Since the sand is consolidated, the thickness is corrected by 10 percent to 20.9 ft. This was then converted to metric 6.37 meters for use in Leeder's equation. Solving Leeder's equation gave a channel width of 117.73 meters or 386.27 ft. Using Lorenz's equation and the channel width of 386.27 ft, the meander belt amplitude was calculated to be 3050 ft. This is the estimated sand body width. This data, along with subsequent calculations, is summarized in Table 2. Sample calculations are contained in Appendix D.

Using the curves in Figure 5 which were calculated probabilities for various sand body widths and various well spacings, a well spacing was chosen. A well spacing for a 50 percent probability of encountering the sand again was used, since definition of the sand body is the object in this application. The well spacing for the first set of data, based on Figure 5, was approximately 2500 ft. This 2500 ft. was used as the desired spacing. Table 3 contains the well spacing for boring 1228 and subsequent borings which encountered the sand.

The 2500 ft spacing results in an arc or semi- circle around boring 1228, having a radius which is that of the well spacing.

Using the borings hypothetically drilled up to this point (numbers 1124 - 1228 in Table 1), sand thickness was kriged using Geo-EAS, a public domain

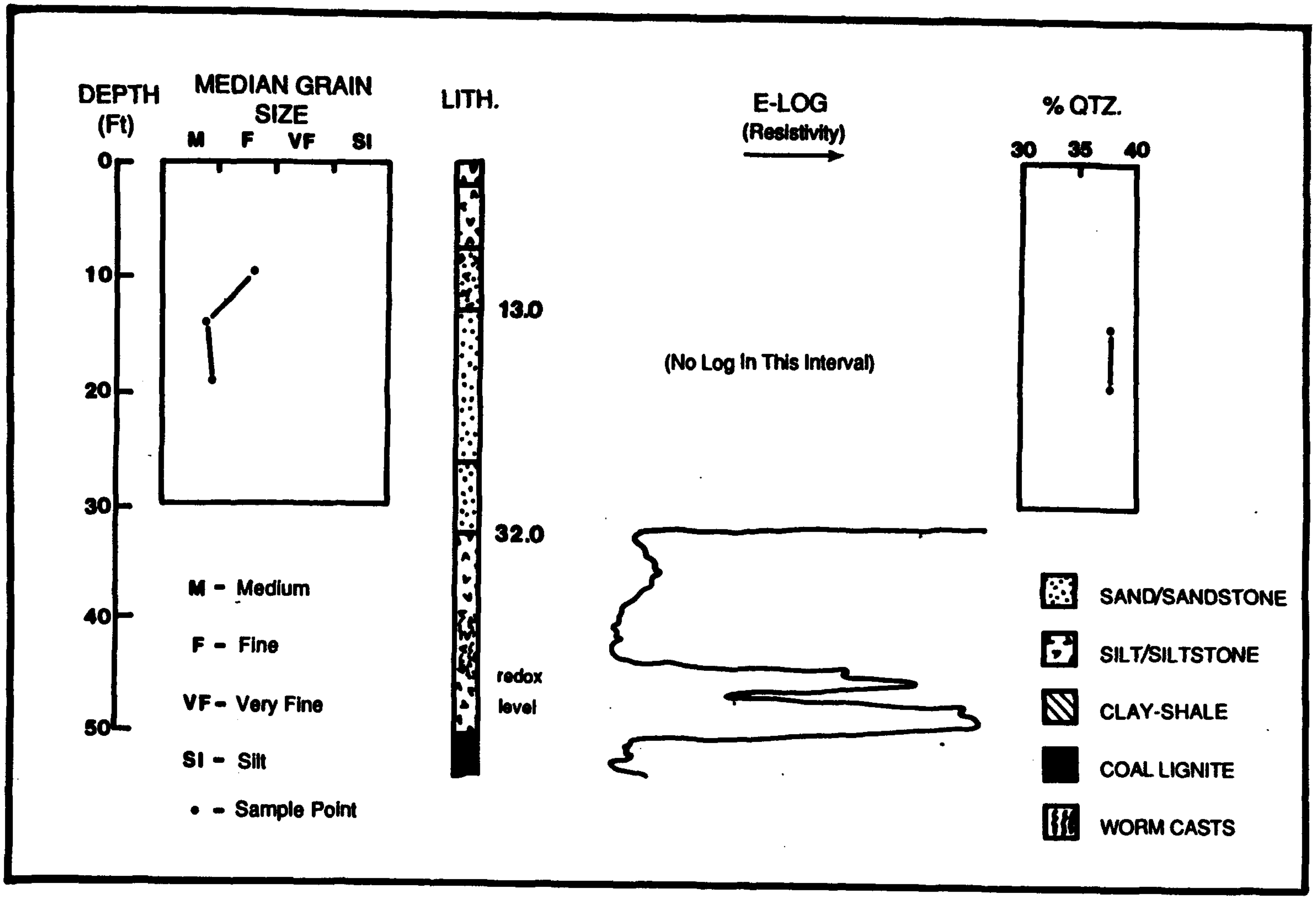

Figure 15. Summary of information for boring 1228

Table 2
Data from Estimating Sand Body Width

Thickness, ft	Corrected Thickness, ft	Metric Thickness, m	Channel Width, m	Channel Width, ft	Approximate Meander Belt Amplitude, ft
19.0	20.90	6.37	117.73	386.27	3050
14.8 (Average)	16.23	4.95	79.84	261.96	2060
19.4 (Average)	21.34	6.5	121.45	398.48	3150

Table 3
Data from Estimating Well Spacing

Boring Number	Estimated Sand Body Width, ft	Probability Percent	Approximate Data Point Spacing, ft
1228	3050	50	2500
757	2060	50	1500
1251	3150	50	2500

computer program produced by the U.S. Environmental Protection Agency. The Geo-EAS program was verified by comparison of the program's results with results of Clark's (1979) kriging of a simulated iron ore deposit. Both are contained in Appendix C. The estimated percentage of iron and the kriging standard deviations for those estimates produced by the Geo-EAS program are similar to Clark's. The slight differences can be attributed to the differing interpretations in the drafting of the contours.

Once kriged, the error for the kriged thickness was obtained, as the kriging standard deviation. The kriging standard deviation was then contoured.

By comparing the kriged standard deviation with the well spacing "arc", some portions of the arc fell in areas where the sand thickness standard deviations were more than the standard deviation of the whole data set, and some portions of the arc fell in areas where the sand thickness standard deviations were less than the standard deviation of the whole data set. The areas on the arc that were in the area where the standard deviations of the sand thickness was greater than that of the whole data set were then hypothetically drilled. The area with the highest standard deviation was selected for the first boring, then additional borings were selected along the arc in the area where the standard deviation of the sand thickness was greater than the standard deviation of the whole data set. These data locations were separated by the same well spacing as the distance from boring 1228. Figure 16 shows the arc for the well spacing from boring 1228, the kriged standard deviations and the locations for the next borings.

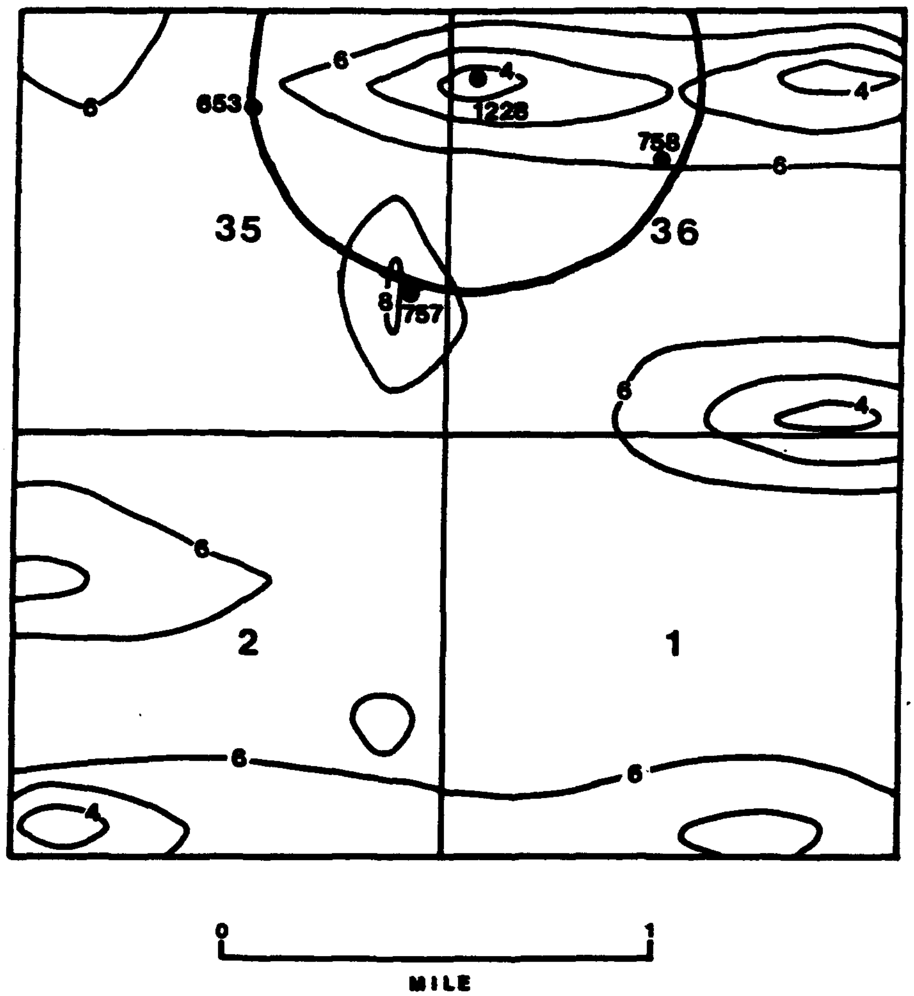

Figure 16. Well spacing arc, as heavy line; contoured kriging standard deviations (in feet) of sand body thickness; and additional boring locations away from boring 1228

The area where the standard deviation is greater than about 6 is considered sufficiently defined, that which is less than 6 is not considered sufficiently defined. This is based on the standard deviation in relation to the standard deviation for the entire sample population. If the specific location standard deviation is greater than the population standard deviation, then the thickness at that location is not sufficiently defined. If the specific location standard deviation is less than the population standard deviation, the thickness is considered reliable (Clark 1979). In this case the standard deviation for the population is 6.28. This standard deviation was obtained by taking the square root of the population variance, which is given by the Geo-EAS program. Table 4 contains the variances given by the Geo-EAS program and their calculated standard deviation for this first set of borings and each subsequent set of borings.

Table 4
Data Set Sand Thickness Population Standard Deviations for the Rocky Mountain Arsenal

Population	Variance, ft^2	Standard Deviation, ft
Set 1	39.48	6.3
Set 2	45.31	6.7
Set 3	83.99	9.2
Set 4	72.30	8.5
Set 5	63.15	8.0
Full Data	194.90	14.0
May's Data	315.81	17.8

The second set of borings were hypothetically drilled. Two did not encounter the target sand, one did. This information is contained in Table 1. Only boring log information was available for these borings, so confirmation of the depositional environment could not be made. The depositional environment was assumed to be the same, meandering fluvial. A new sand thickness was estimated from the average thickness of the two borings which had encountered the sand. A new sand body width and subsequent spacing was calculated. This information is shown in Table 2.

Thickness was again kriged, obtaining the standard deviation of the sand body thickness, which was contoured. An arc from boring 757, which encountered the sand, only allowed for one additional boring in an area where the standard deviations of the sand thickness was greater than the standard deviation of the whole data set, the highest standard deviation on the arc. Figure 17 shows this. Table 4 contains the population standard deviation as "Set 2".

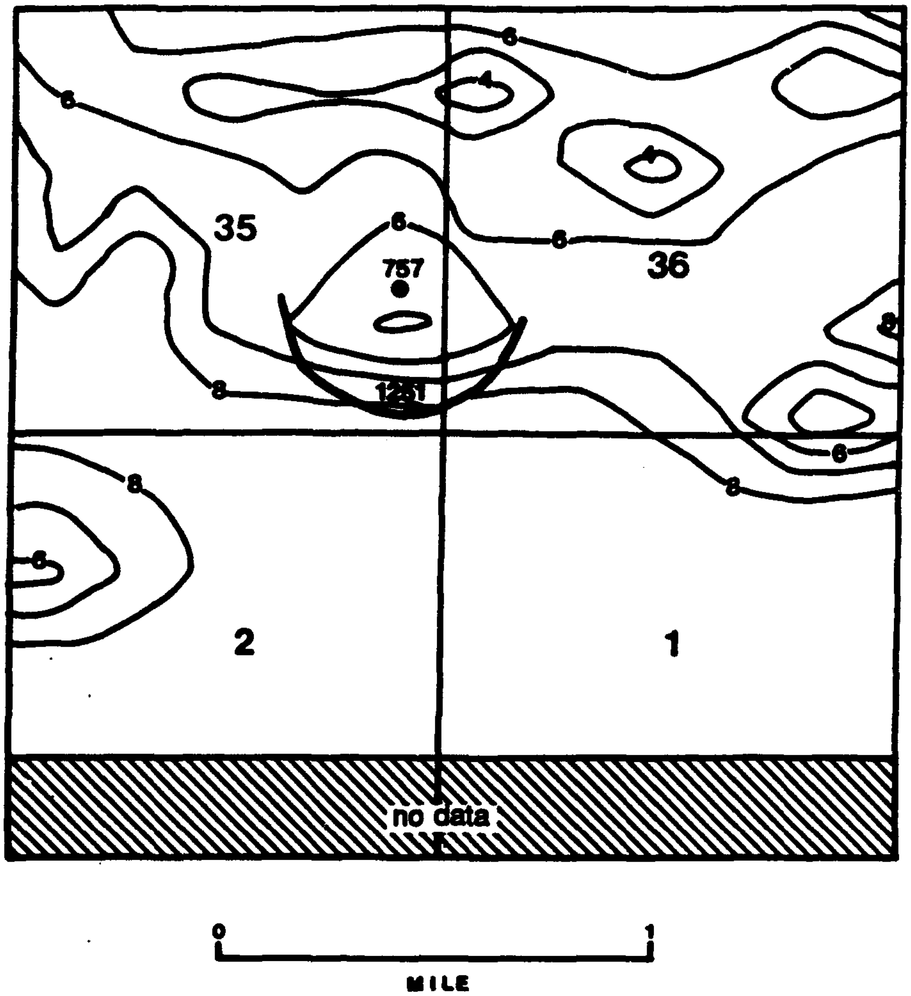

Figure 17. Well spacing arc, as heavy line; contoured kriging standard deviations (in feet) of sand body thickness; and additional boring locations away from boring 757

The new location was hypothetically drilled. Based on stratigraphic relationships, it was determined that the target sand was encountered. This boring, 1251, had sufficient information to confirm the environment of deposition. This information is summarized in Figure 18. The stratigraphic section in the sand sequence is almost identical to that described for boring 1228. A stream had cut down into underlying dark gray silty clay shale.

A new average thickness was calculated, giving a new sand body width and subsequently a well spacing of approximately 2500 ft, the same spacing as obtained from the first data set. These are shown in Tables 2 and 3.

Thickness was kriged and standard deviation contoured. The area of highest standard deviation on the arc for well spacing from boring 1251 could not be hypothetically drilled, because there were no usable borings in that area. Three borings with approximately the same well spacing along the arc, as from boring 1251, were chosen. These were in areas where the standard deviations were greater than the standard deviation of the whole data set.

There are fewer borings in the lower portion of the site that penetrate the target sand, because it is becoming deeper with the direction of dip.

Two of the additional borings did not encounter the target sand, one did, as shown in Table 1. This is shown in Figure 19.

This set of borings was kriged showing the area containing the sand body to be defined, but due to the variation in the standard deviation, three more boring sites were chosen in areas of relatively higher standard deviation in an effort to make the standard deviation more uniform. This is shown in Figure 20.

These areas are approximately the same spacing from several wells as the last derived well spacing.

These sites were hypothetically drilled, none encountering the target sand. These borings were added to the data set and the thickness was kriged. The resulting standard deviations are fairly uniform. This is shown in Figure 21.

With the data used in the hypothetical drilling program (Table 1), the kriged thickness was contoured. This is shown in Figure 22. The purpose of contouring the kriged sand thickness was to compare with that already produced by other studies. Although similar in some respects, the test case was noticeably different from that of May's (1985) and ESE's (EBASCO 1989). These are shown in Figures 23 and 24 respectively.

Since neither used the Geo-EAS program, May's (1985) and ESE's (EBASCO 1989) sand thickness data were kriged with the Geo-EAS program. The data point (boring) locations are listed in Appendix E and are shown in Figures 25 and 26. The resulting sand thickness contours are shown in Figures 27 and 28. The kriging standard deviations for these two data sets were also contoured and are shown in Figures 29 and 30.

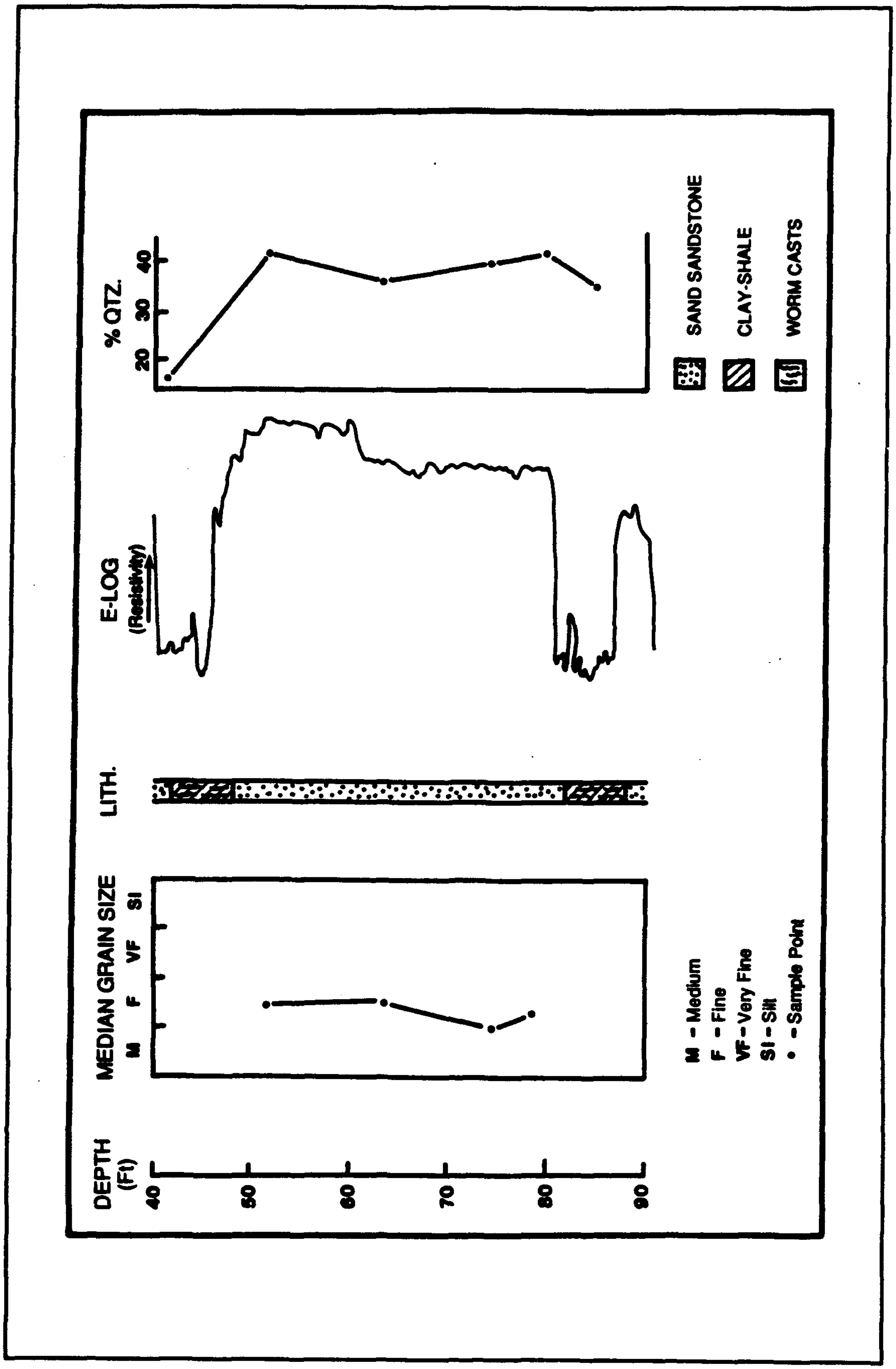

Figure 18. Summary of information for boring 1251

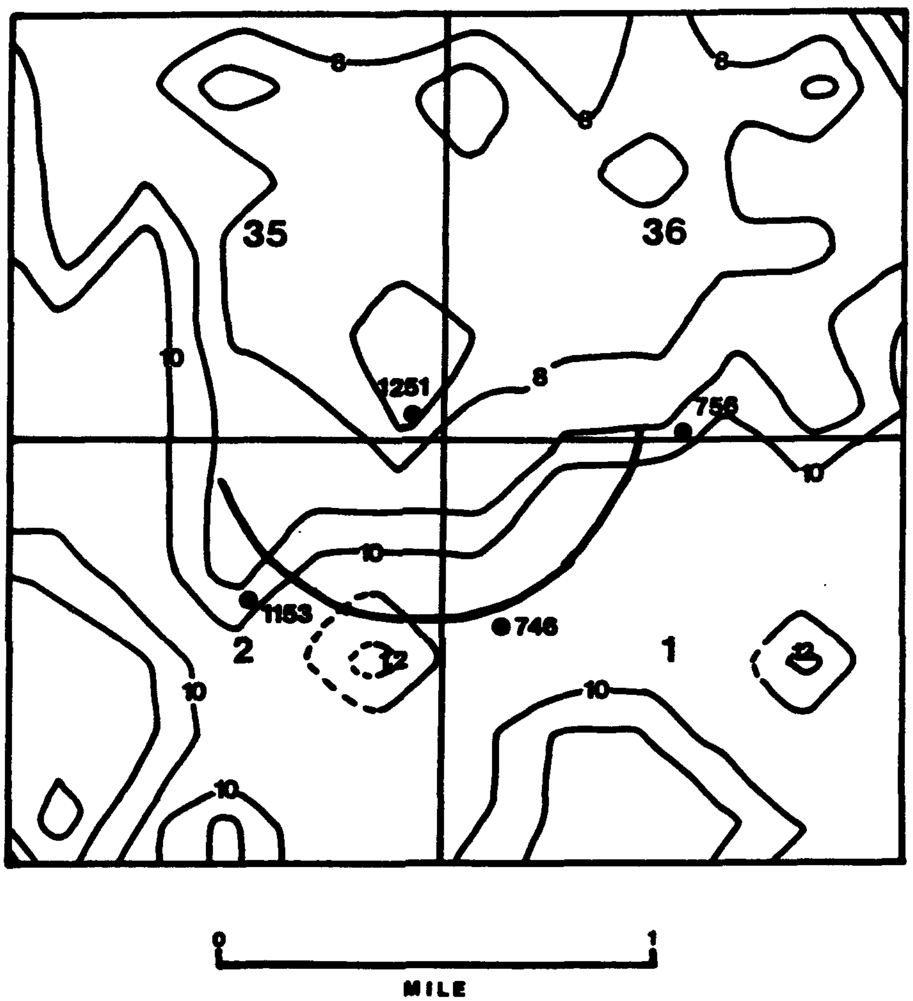

Figure 19. Well spacing arc, as heavy line; contoured kriging standard deviations (in feet) of sand body thickness; and additional boring locations away from boring 1251

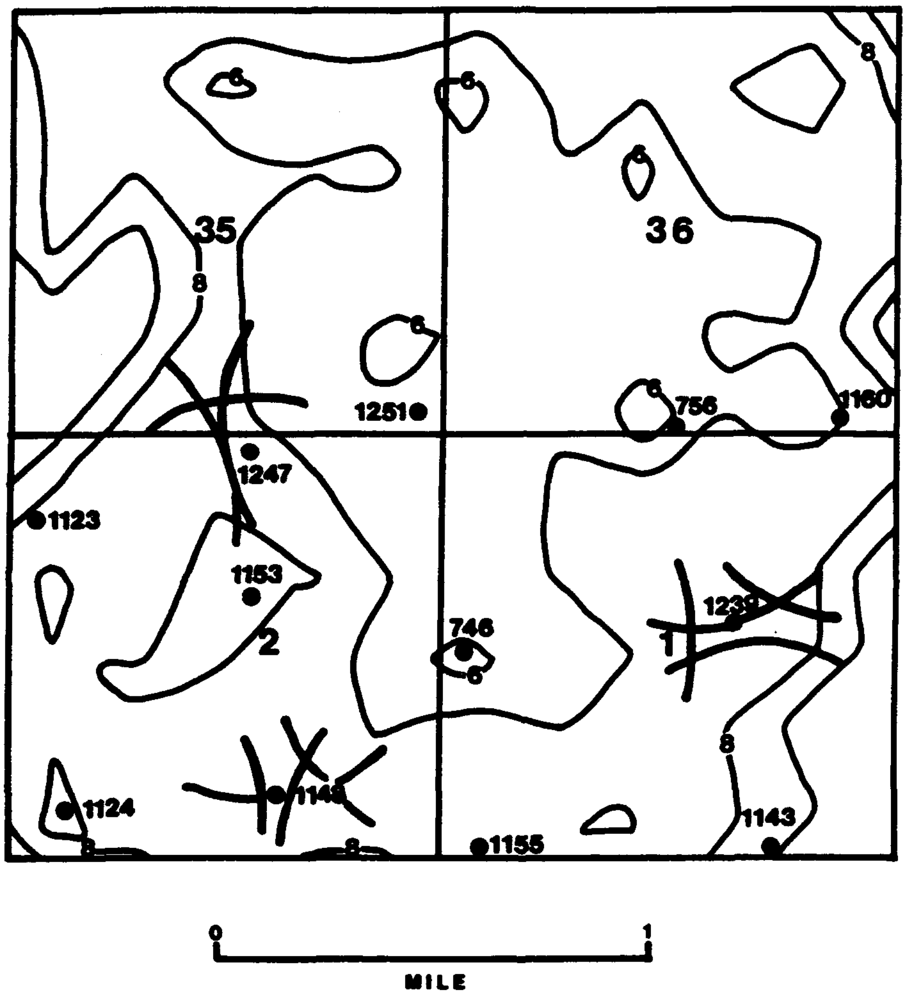

Figure 20. Well spacing arcs, as heavy lines; contoured kriging standard deviations (in feet) of sand body thickness; and additional boring locations

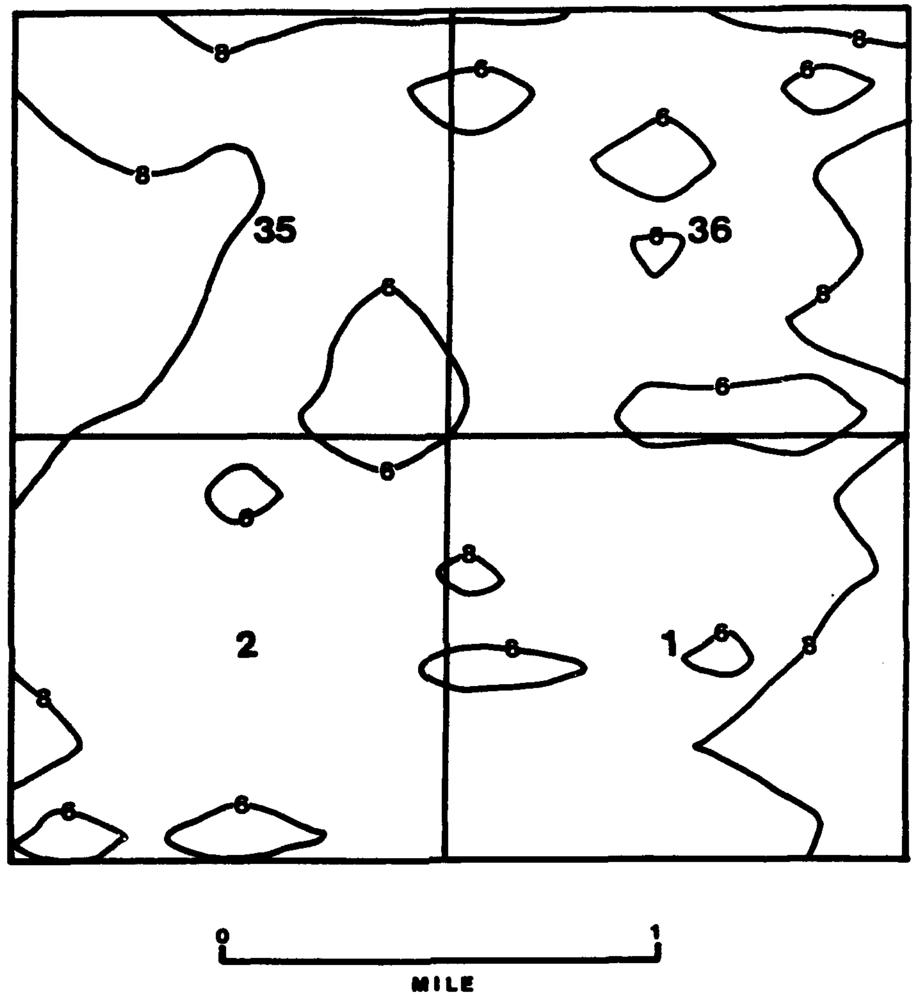

Figure 21. Kriging standard deviations of thickness, in feet, for full set of borings in Table 1 (corresponding thicknesses are shown in Figure 22)

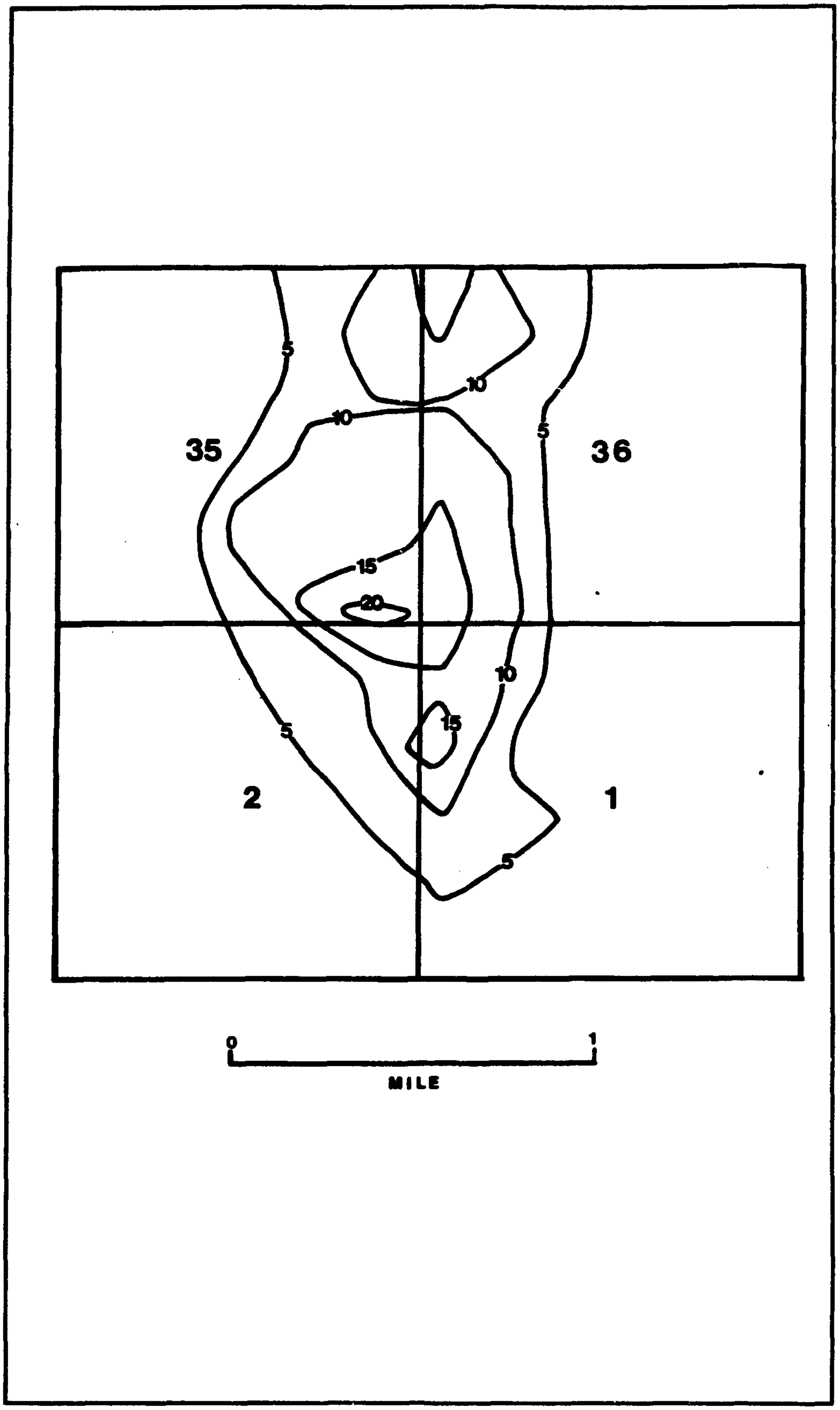

Figure 22. Kriged sand thickness, in feet

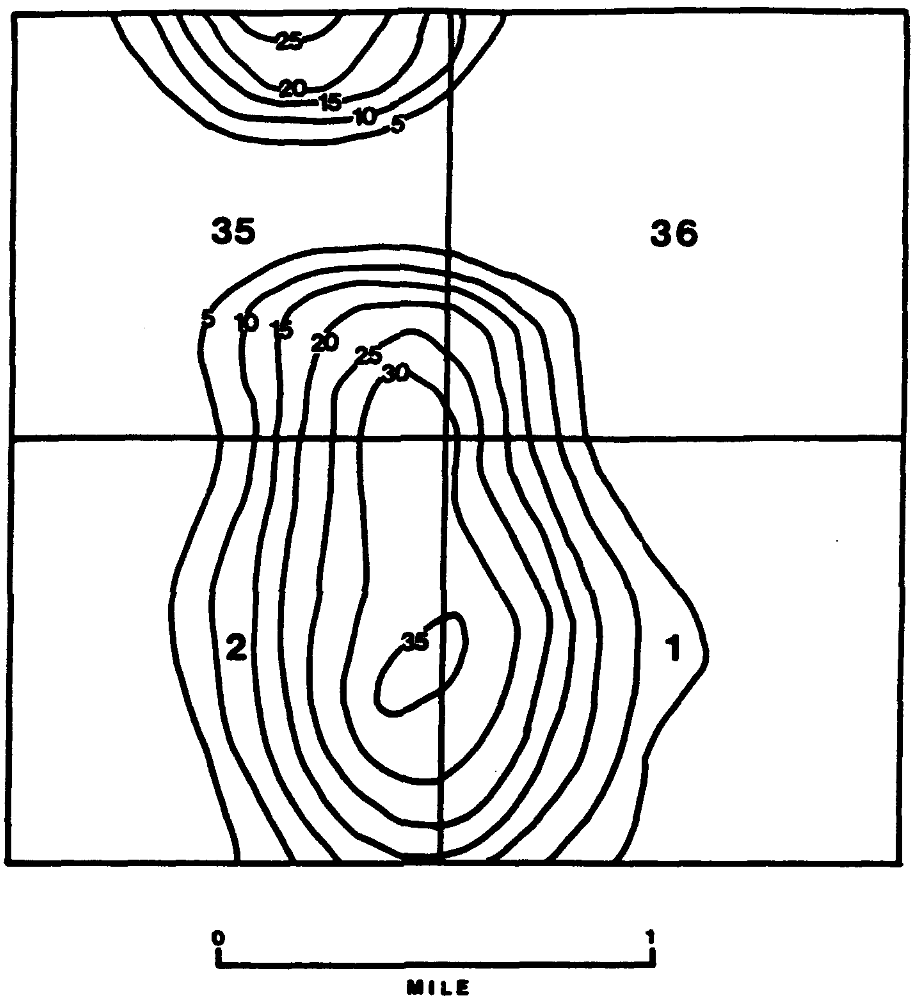

Figure 23. May's sand thickness, in feet (after May 1985)

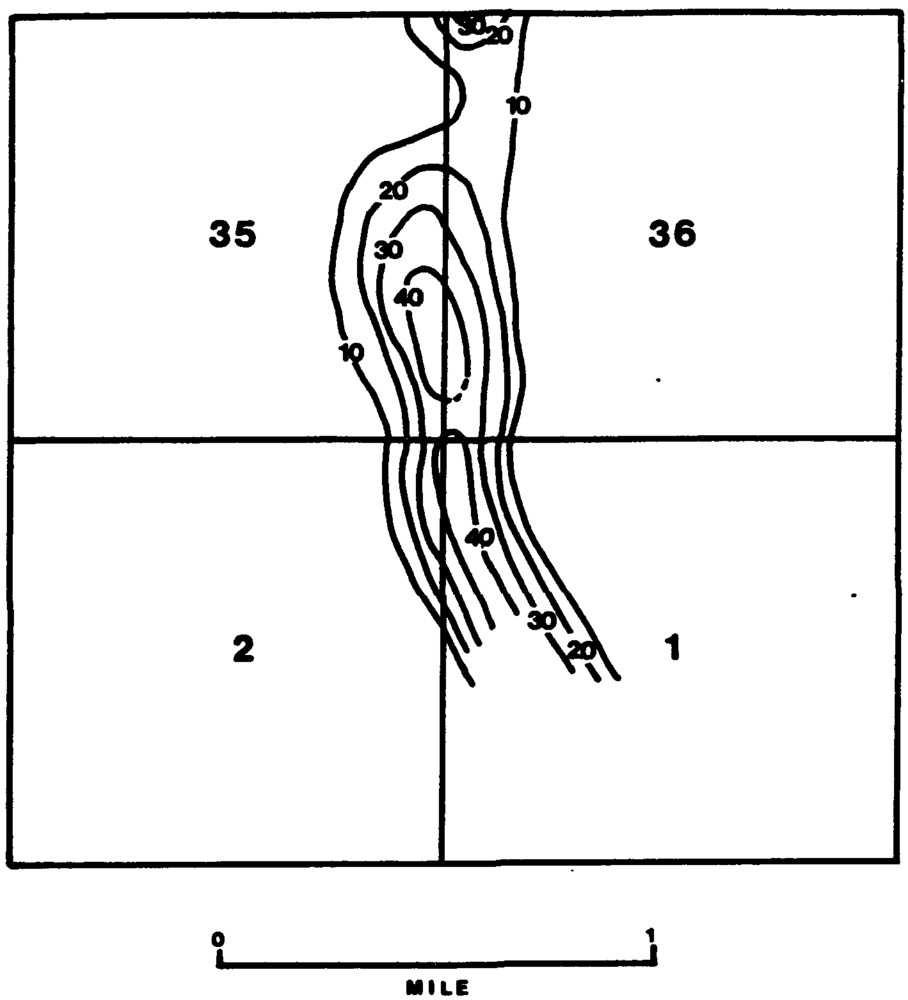

Figure 24. ESE's sand thickness, in feet (after EBASCO 1989)

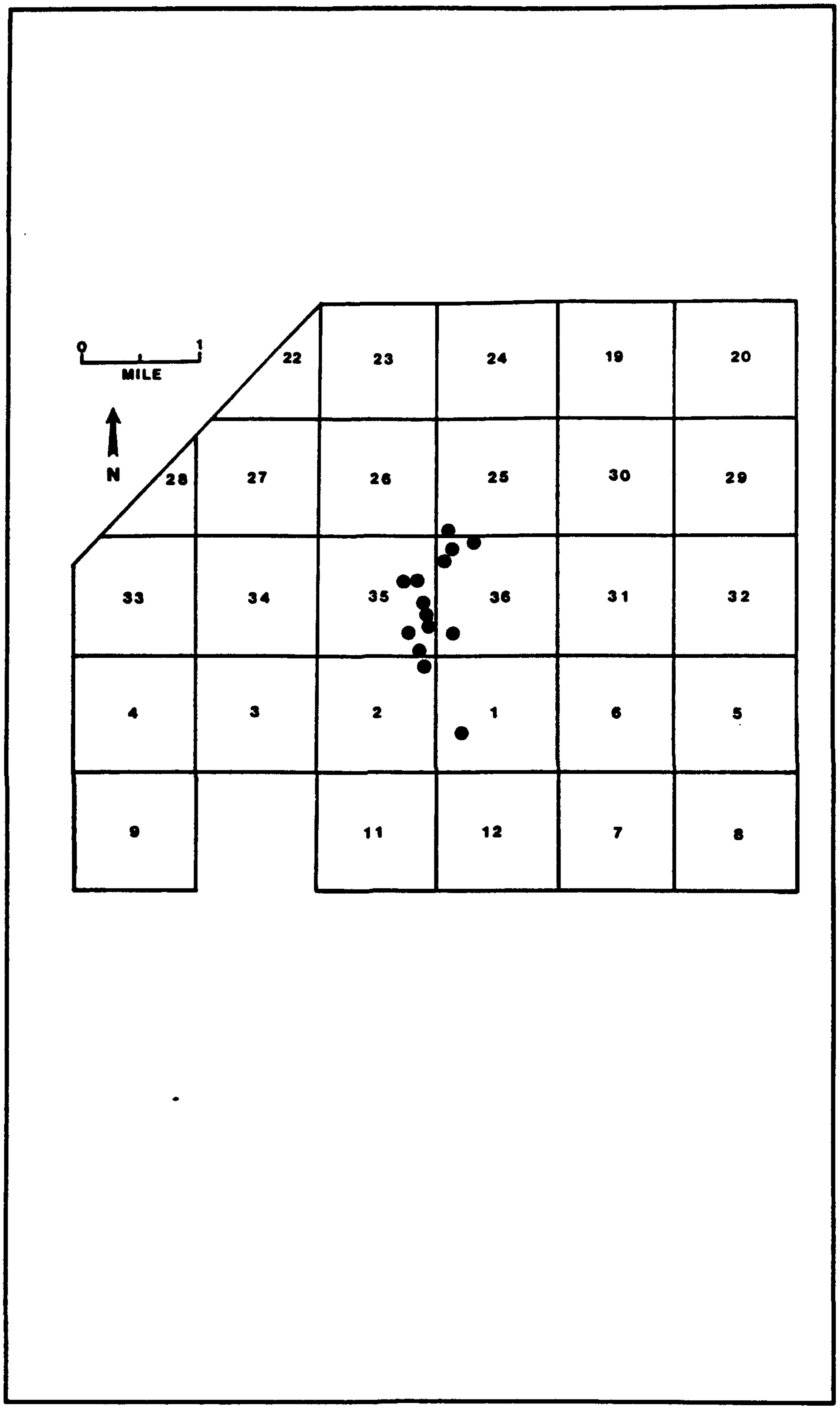

Figure 25. Location of May's data points used for kriging (after May 1985)

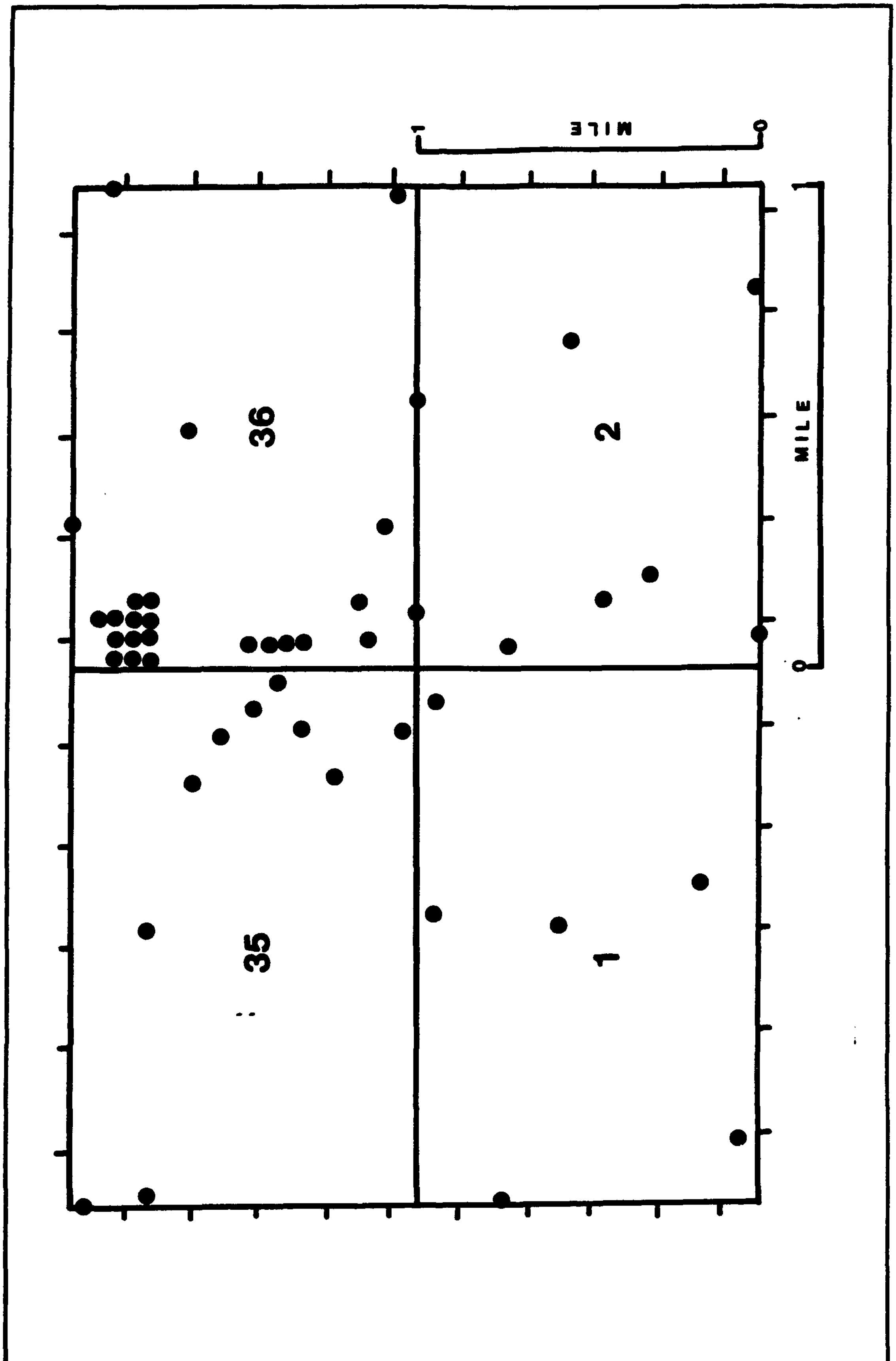

Figure 26. Location of all data points used for kriging at the Rocky Mountain Arsenal

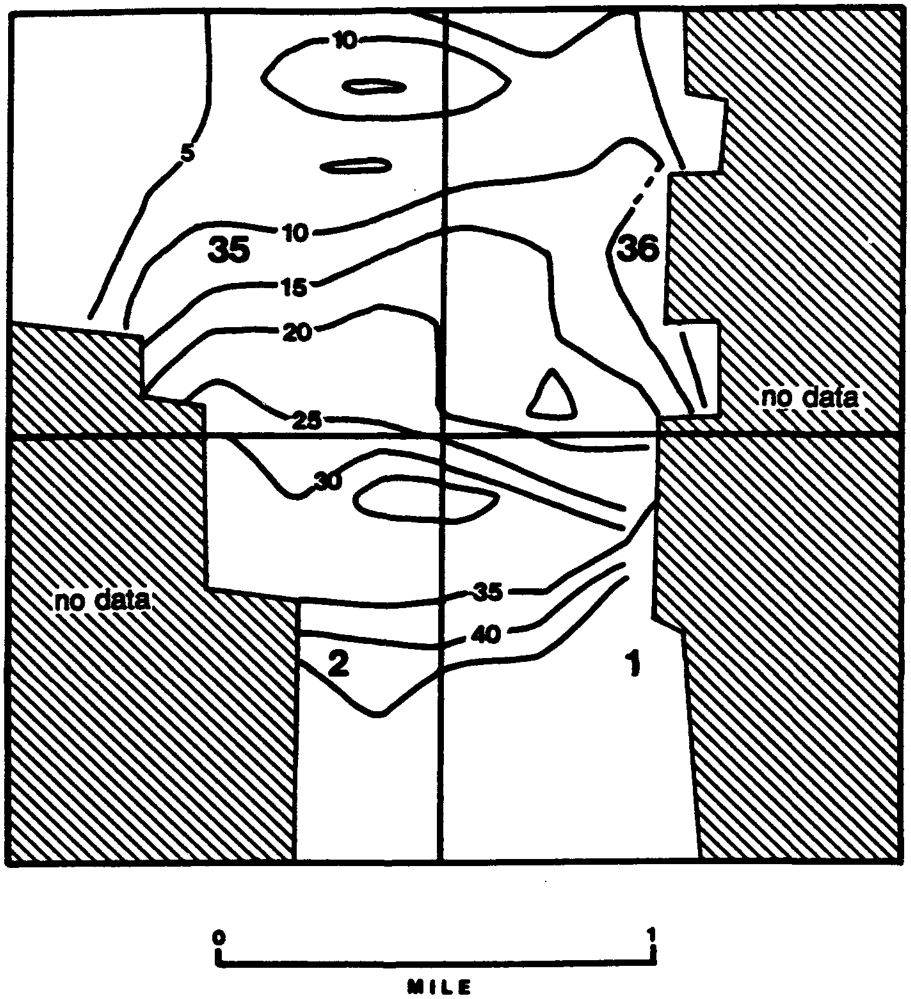

Figure 27. May's kriged sand thickness, in feet

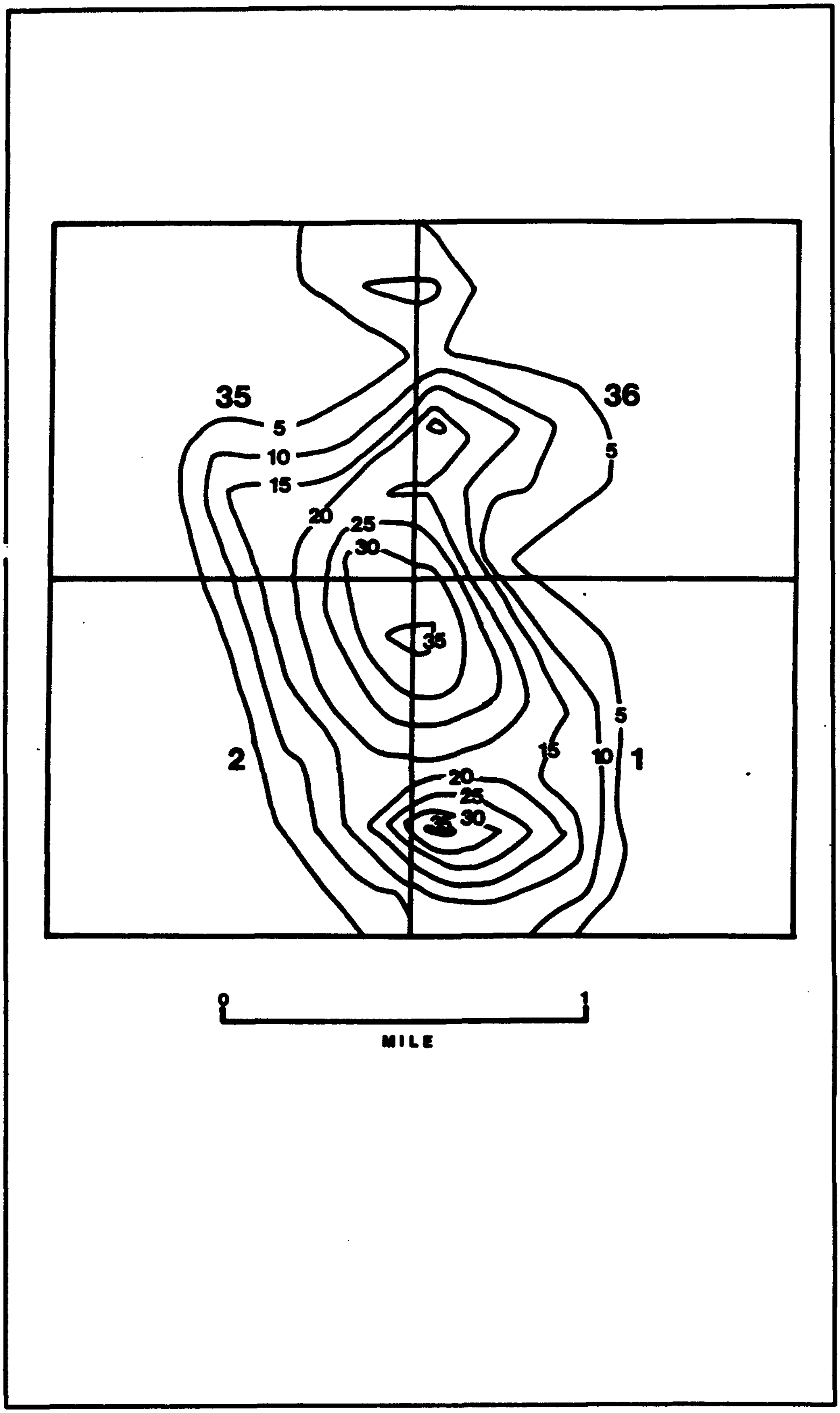

Figure 28. Kriged sand thickness, in feet, for all data at the Rocky Mountain Arsenal

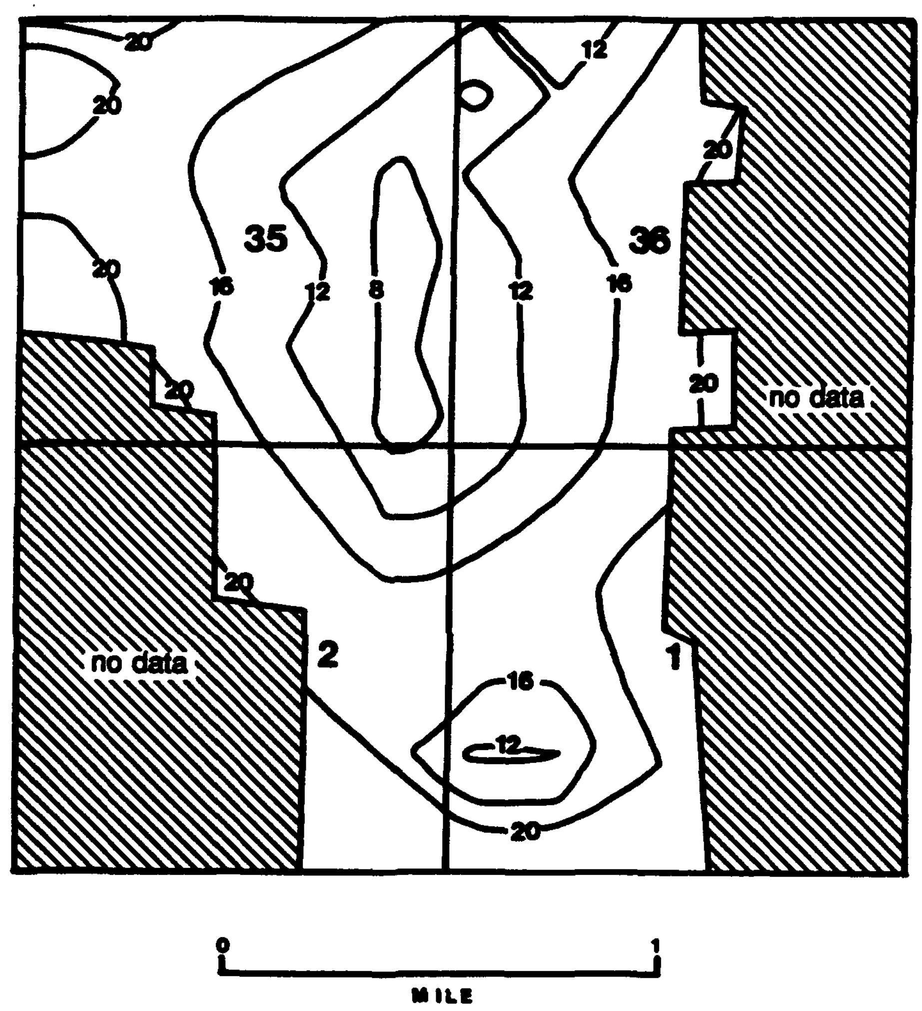

Figure 29. May's kriging standard deviations, in feet

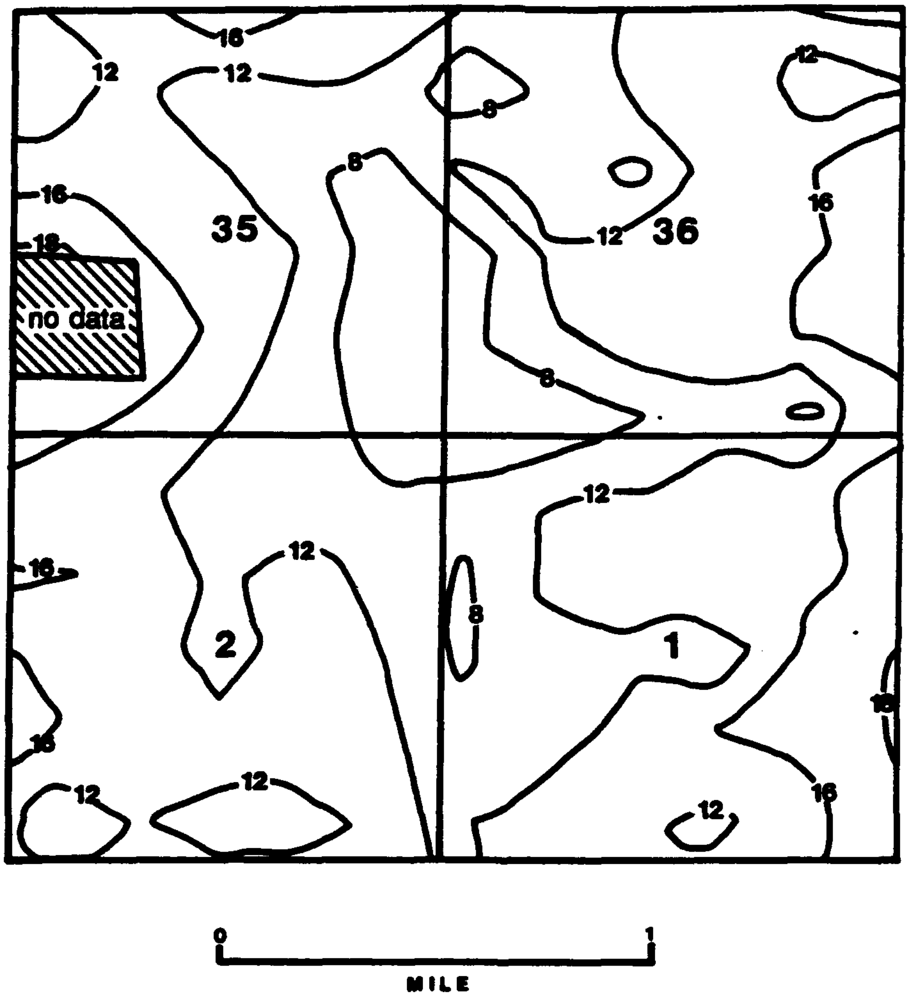

Figure 30. Kriging standard deviations, in feet, for all data at the Rocky Mountain Arsenal

When comparing the kriged standard deviation to the sand thickness standard deviations, in both cases, May's and all the data, the thickness standard deviations are greater than the standard deviation of the whole data sets in the southern portions of the site. This is due to the lack of sufficient borings penetrating the depth necessary to encounter the target sand in that area of the site. The variances and standard deviations for the sample populations are given in Table 4.

From these results, it would appear that the hypothetical borings had defined the sand body better than May's (1985) data or all the available data from EBASCO (1989).

However, when making confidence statements of May's (1985), and of all the data, a different conclusion is obvious. The confidence statement is made for sand thickness which is derived from the kriging. This is commonly given as 95 percent confidence with a + or - factor which is double the standard deviation.

This results in a + or - factor which is greater than the sand thickness for the test case, even though the sand thickness standard deviations were less than the standard deviation of the whole data set. Table 5 shows the confidence of locations shown in Figure 31 and whether the sand thickness standard deviation was less than the standard deviation of the whole data set (reliable) or not, for selected locations in the test case, as well as for May's (1985) data, and all the data.

The obvious solution to the confidence statement problem, is to add more boring locations. However, since all the data available has already been used, with the sand thickness standard deviations being greater than the standard deviation of the whole population in some areas, there are not enough boring locations to be able to do this.

Another approach had to be taken to further investigate this portion of the rationale for exploration. This approach will be described in the Supplementary Case Study section.

Despite the confidence statement problem, the rationale for exploration did follow the target sand through the site. This can be seen in Figure 32 which shows the subtle shift of the boring locations in the direction of the target sand.

Another problem was encountered during the application of the rationale for exploration. This was a problem of justifying the variograms for the kriging with limited data. Variograms usually contain considerably more data than that of the boring locations of the hypothetical drilling.

A variogram was obtained with the Geo-EAS program for each data set. The same type and model was obtained in each case. These are contained in Appendix F. To justify the types and models as usable for these data sets,

Table 5
Confidence Statements of Selected Locations at the Rocky Mountain Arsenal

Location	Reliable	95 Percent Confidence for Thickness, ft
Test Case Data		
1	Yes	5 ± 16
2	Yes	5 ± 16
3	Yes	5 ± 12
4	Yes	5 ± 12
5	Yes	5 ± 12
6	Yes	5 ± 12
7	Yes	0 ± 14
May's Data		
1	Yes	7.5 ± 34
2	Yes	8 ± 28
3	Yes	32.5 ± 36
4	Yes	7.5 ± 34
5	Yes	20 ± 30
6	No	45 ± 36
7	No	>45 ± 40
All Data		
1	No	0 ± 32
2	Yes	0 ± 26
3	Yes	5 ± 22
5	Yes	0 ± 24
6	Yes	17.5 ± 20
7	No	15 ± 24

some modern streams were used to obtain variograms from larger data sets. This will be more fully described in the Geostatistics section.

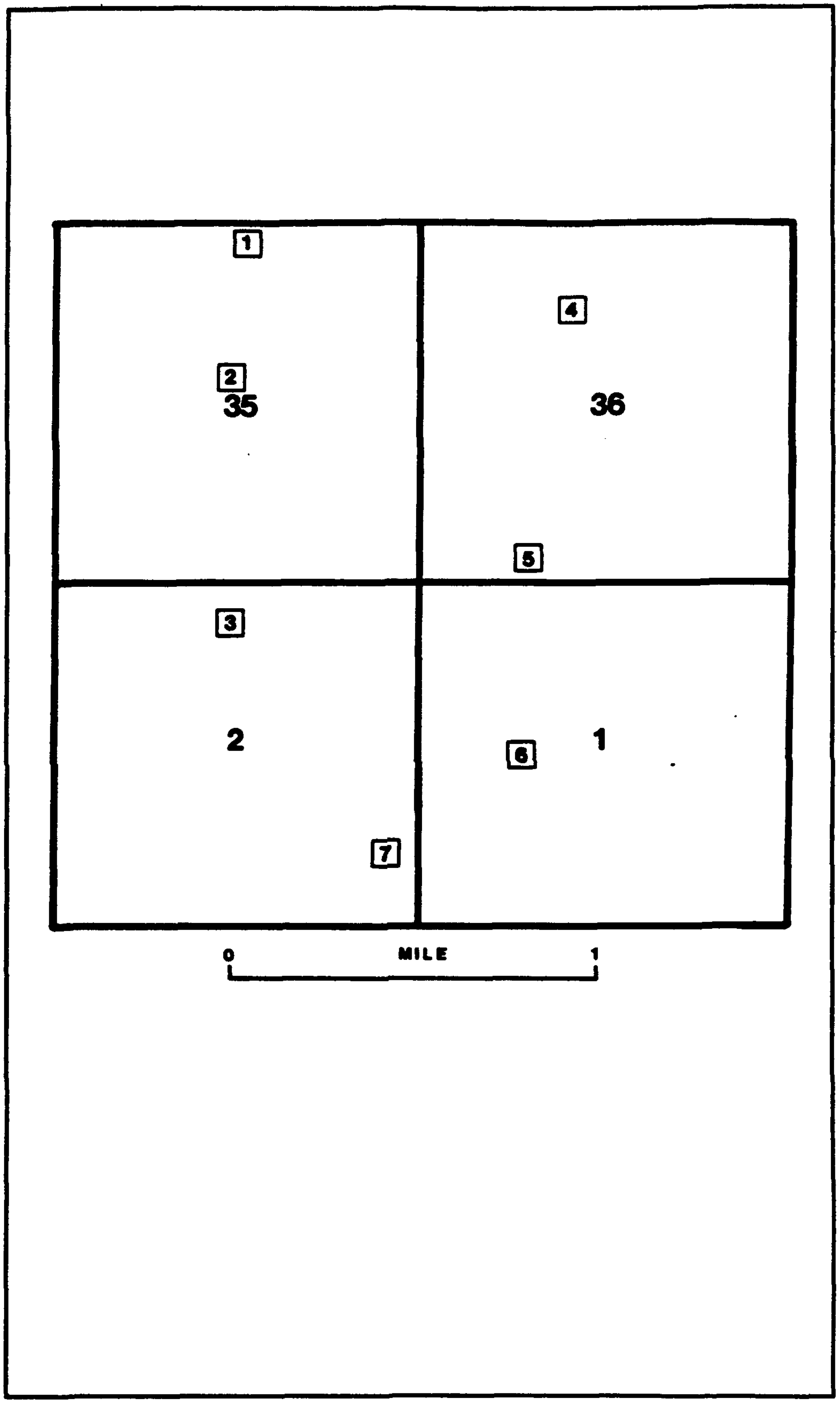

Figure 31. Location of selected confidence statements

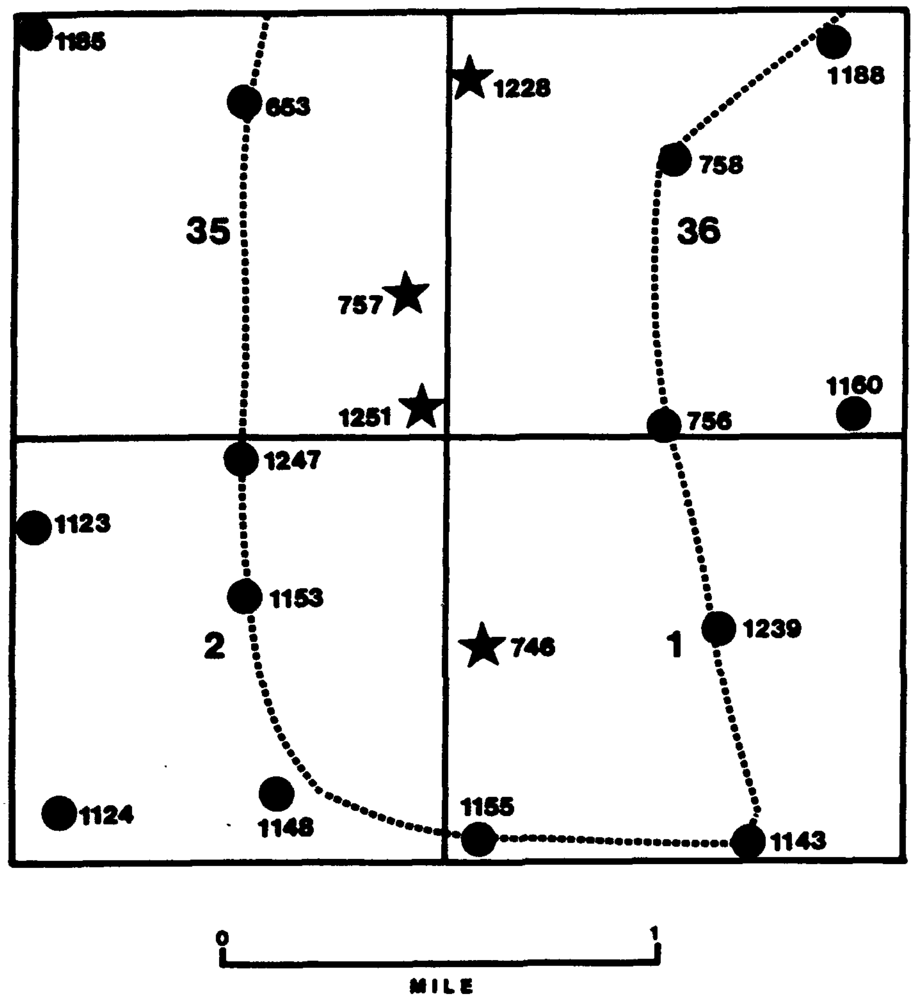

Figure 32. Boring locations defining the "target" sand: stars are borings which encountered sand, the dark circles did not

4 Stratigraphic Interpretations

This section provides the details of establishing and confirming the environment of deposition for the "target" sand body at the Rocky Mountain Arsenal and the reason for thickness variation of and termination of that "target" sand body.

Interpretations

From various data available from borings at the Rocky Mountain Arsenal, the environment of deposition of the "target" sand was determined. As stated in the previous section, this data included grain size analysis, X-ray diffraction analysis, geophysical logs, and detailed core descriptions. The information available for each boring of the hypothetical drilling was used to define the sand body. This information is shown in Figure 33.

Core descriptions from borings, geophysical logs, and grain size analyses were available for the four-numeral boring locations with the exception of boring 1239, which had no core description. Additionally, borings 1228 and 1251 contained grain size statistical analyses and X-ray diffraction analyses. Both of those boring locations intersected the "target" sand during the hypothetical exploration drilling.

Information for the three-numeral boring locations was obtained from cross-section and tabular data contained in previously produced geological reports.

The cross-section plus tabular data and the available core descriptions were used to produce the lithologic characterizations at the boring site locations. These are shown for individual borings in a portion of Figures 15 and 18 and in cross- sections contained in Figures 34, 35, and 36. Core descriptions are contained in Appendix G. Cross-sectional and tabular information are contained in Appendix H.

Little sedimentary structure was described in the cores. This may have been due to the poorly consolidated condition of the sand combined with the method of sampling. Split spoons and pitcher samplers were pushed into the sediment for sampling. This type of sampling of poorly consolidated saturated

Boring Number	Other Number	Boring Log	Grain Size Analysis	Geophysical Log	X-Ray Diffraction Analysis
1124	SP13	X	X	X	
1155	SP15	X	X	X	
1143	SP16	X	X	X	
1160	SP02	X	X	X	
1188	E01	X	X	X	
1123	SP08	X	X	X	
1185	N06	X	X	X	
1228	AP01	X	X	X	X
746	--	Tabular and Cross-Sectional Information Only			
1153	SP09	X	X	X	
756	--	Tabular and Cross-Sectional Information Only			
1251	AP25	X	X	X	X
653	--	Tabular and Cross-Sectional Information Only			
757	--	Tabular and Cross-Sectional Information Only			
758	--	Tabular and Cross-Sectional Information Only			
1247	AP21	X	X	X	
1148	SP12	X	X	X	
1239	AP12		X	X	

Note: X - Available

Figure 33. Available information for specific boring locations at the Rocky Mountain Arsenal

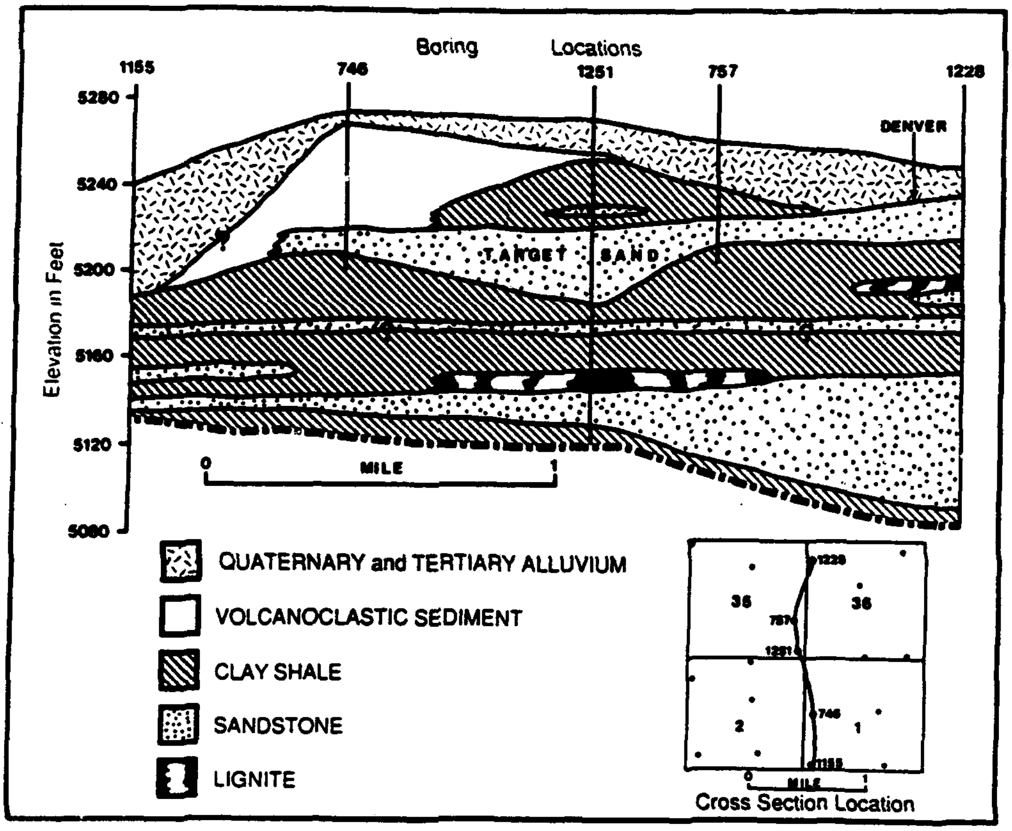

Figure 34. Cross-sectional view down dip through the "target" sand body at the Rocky Mountain Arsenal

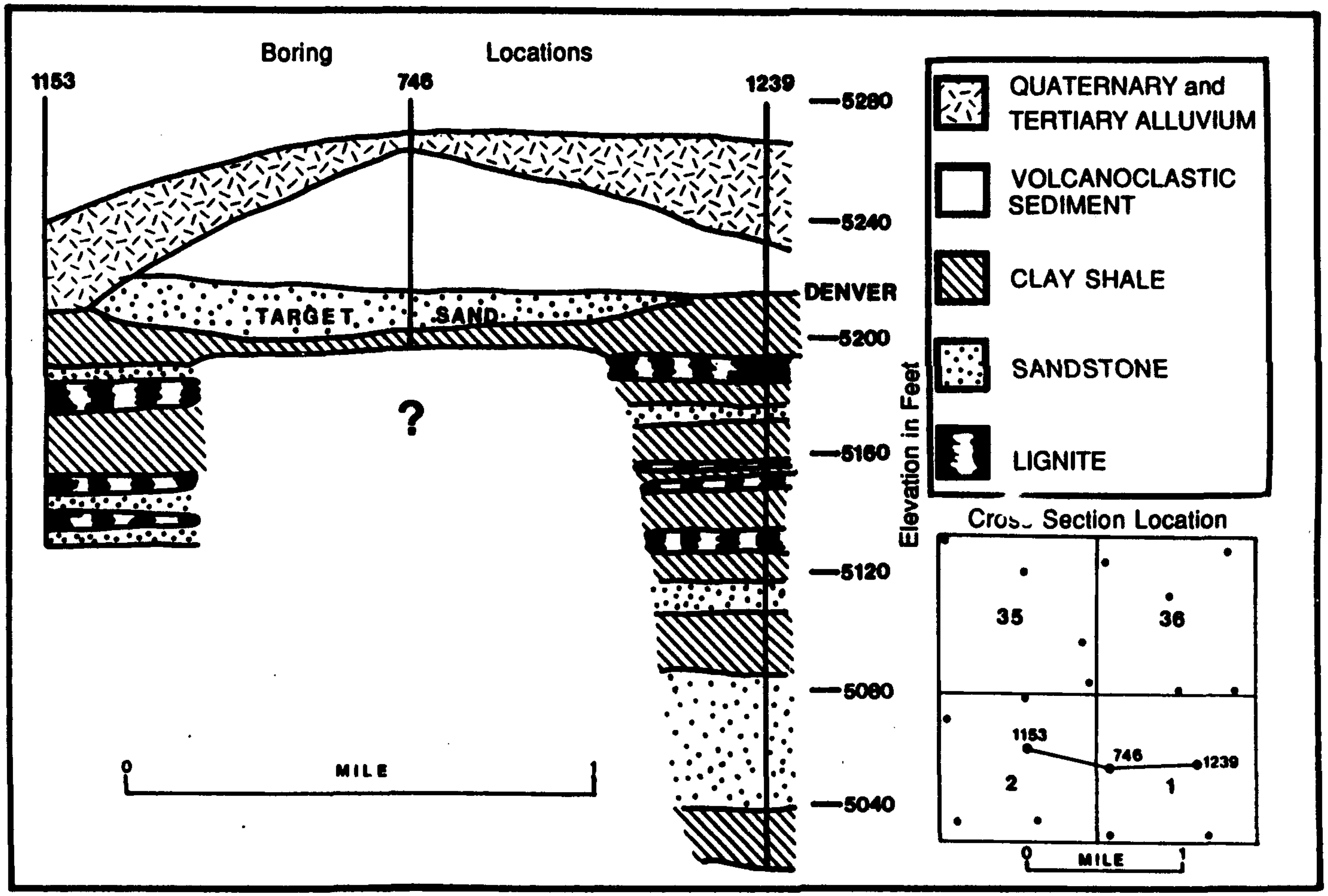

Figure 35. Northern cross-sectional view across the "target" sand body at the Rocky Mountain Arsenal

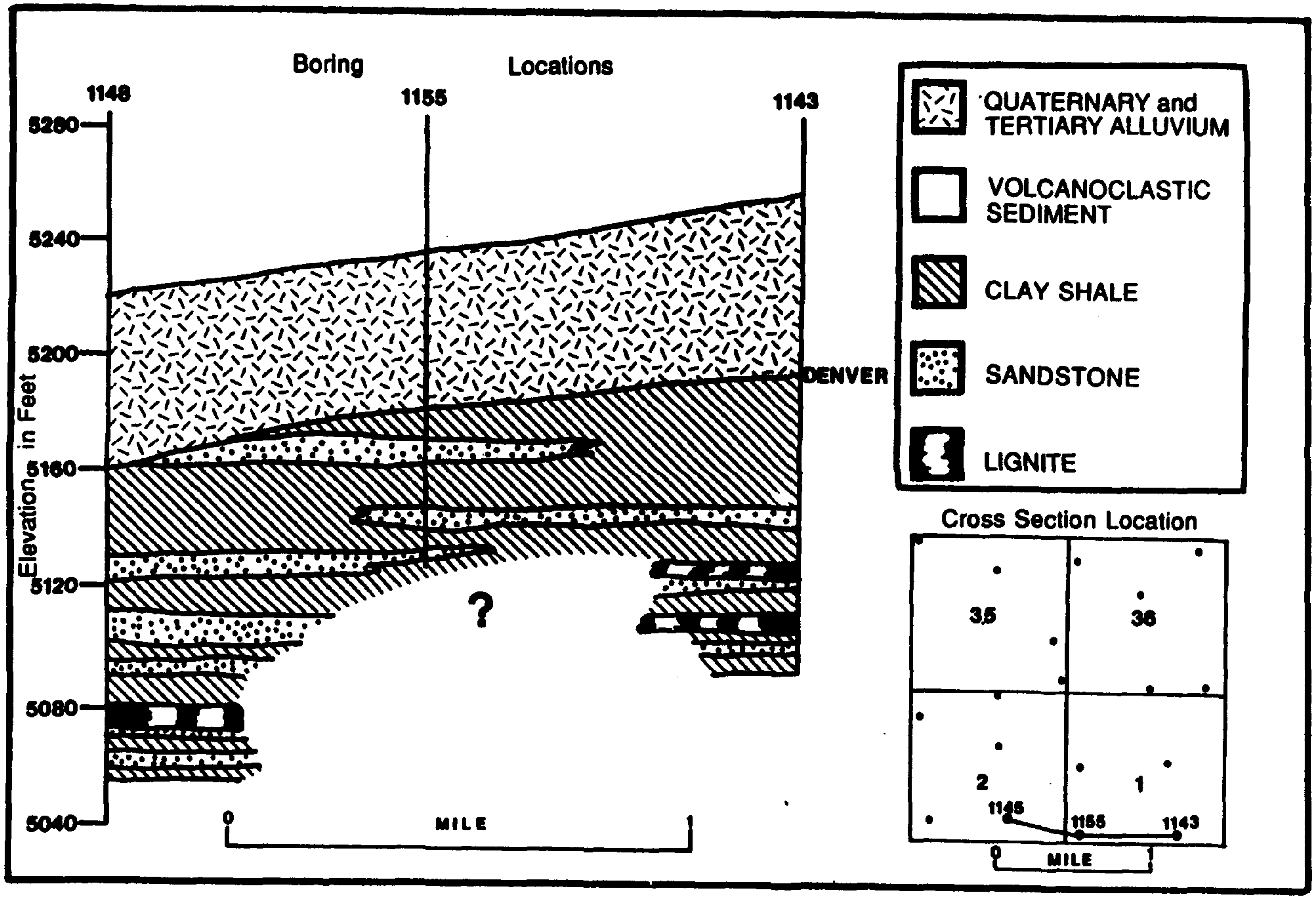

Figure 36. Southern cross-sectional view across the "target" sandy body interval at the Rocky Mountain Arsenal (Target sand body is not present)

sands would destroy any faint structure that might be present. The sand is called massive in some descriptions, however. A massive sand should be expected in the basal portions of the fluvial sequence due to higher transport energy in the deeper portion of the channel. Although any sedimentary structures that might have been present in the sand were not obtained, the lithology was obtained and was instrumental in interpreting the depositional environment. This is exemplified by looking at the cross-sections in Figures 34, 35, and 36. Figure 34 shows the "target" sand body in the direction of dip. It should be noted that the top of the sand body is relatively smooth, dropping in elevation in the direction of dip. The contact of this sand with the underlying clay is sharp, but irregular. The bottom of such sand bodies are often irregular, but the irregularity in the cross-section may be due to the location of the boring within the width of the sand body. Boring 1251 would be in the thickest portion, while borings 1228 and 746 are closer to the edges of the sand body, with boring 757 being even closer to the edge of the sand body. The cross-section in Figure 34 also shows why the "target" sand does not continue through the southern most boundary of the site. Quaternary and Tertiary alluvial deposits have replaced the sand, indicating that it was eroded and removed by the Quaternary and Tertiary processes which deposited the alluvium.

The cross-section in Figure 35 shows that the western side of the sand may also have been terminated by the Quaternary and Tertiary alluvium.

The cross-section in Figure 36 shows that the Quaternary and Tertiary alluvium is continuous along the southern boundary at the elevation where the "target" sand would be expected.

The electrical resistivity portion of the geophysical logs were helpful in determining relative grain sizes and establishing contacts between different geological materials as depicted in Figure 37 and a portion of Figures 15 and 18. The geophysical logs that were available on the borings of the hypothetical drilling program are contained in Appendix I.

Vertical distribution of the grain size within the "target" sand was determined by sieve analyses from the core samples, taken at various depths within the sand. Only two locations, borings 1228 and 1251, which encountered the "target" sand in the hypothetical exploration, had sieve analyses in the "target" sand. The gradation curves for the analyses for these two borings are contained in Appendix J. The median grain size of each analysis was plotted with depth for each boring and is shown in a portion of Figures 15 and 18.

In addition to the sieve analyses, the inclusive graphic standard deviation was used as a measure of sorting. Using Folk's (1980) formula:

$$\frac{\varnothing 84 - \varnothing 16}{4} + \frac{\varnothing 95 - \varnothing 5}{6.6}$$

to include 90° of the cumulative percent distribution of grain size in a sample ($\phi = -\log_2$ mm). The $\phi 84$ is the ϕ value where the cumulative curve crossed the 84 percent line. Alluvial deposits are moderately to poorly sorted. This statistical analysis was performed on the two borings, 1228 and 1251, which encountered the "target" sand and which

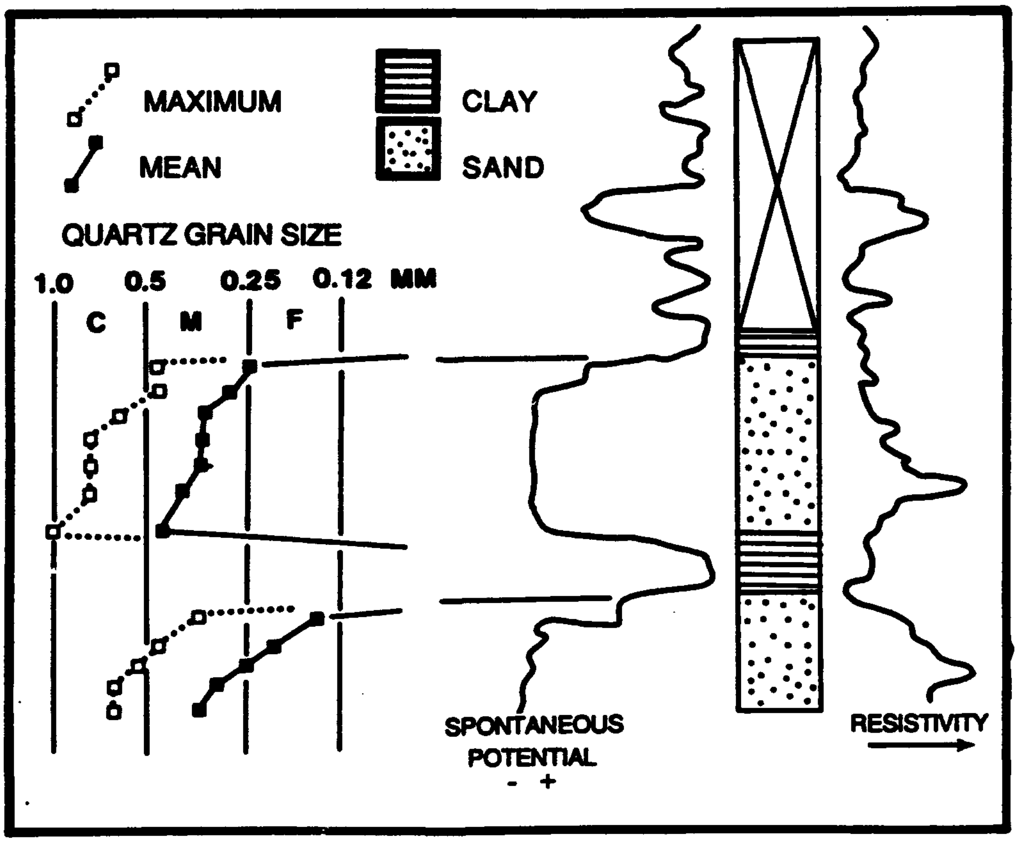

Figure 37. Appearance of geophysical log curves through typical fluvial deposits (after Berg 1986)

had sieve analyses. The determination of sorting is contained in Table 6. As expected for a fluvial sand, the samples from boring 1228, which were taken from the sand itself show moderately well sorting and the sample from boring 1251, which was taken from the upper portion of the fluvial sequence shows poor sorting.

Table 6
Sorting as Determined from Inclusive Standard Deviation

Boring Number	Depth, ft	Sample Number	Standard Deviation	Sorting
1228	14.0 - 15.3	4	0.89	Moderately Well
1228	19.0 - 20.0	5	0.73	Poorly
1251	40.0 - 41.4	15	1.36	Poorly

This tendency to change toward the upper portion of the sequence is supported by the increase in matrix material and decrease in quartz in the upper portions of the sequence. X-ray diffraction analysis was performed on samples from different intervals of the two borings, 1228 and 1251, which encountered the "target" sand. The results are summarized in Table 7 and are shown in a portion of Figures 15 and 18. Boring 1251 shows a decrease in percentage of quartz at the upper portion of the sequence. Both borings show around 40 percent quartz through the middle and lower portions of the sand.

Table 7
X-Ray Diffraction Analysis Results

			Indices	
Boring Number	Depth, ft	Percent Quartz	I_{101}	I_{334}
1228	14.0 - 15.3	38	15	78
1228	19.0 - 20.0	38	15	78
1251	40.9 - 41.4	15	10	--
1251	51.5 - 52.0	42	17	--
1251	63.2 - 63.7	37	16	--
1251	74.3 - 74.8	39	16	81
1251	78.3 - 78.8	42	17	--
1251	80.0 - 80.5	35	16	--

The information as just described, when available, was compiled for each boring in the hypothetical drilling that encountered the "target" sand as shown in Figures 15 and 18 for borings 1228 and 1251 respecti[illegible] This

information was then compared to that for various depositional environments which can form sand bodies, shown in Figure 2. From the comparison, the diagnostic characteristics of the fluvial channel environment were met by the "target" sand with the exception of the sedimentary structures, which were not obtained. Figure 38 shows the diagnostic characteristics for a fluvial channel sand.

The sand penetrated by boring 1228 is interpreted to be a fluvial sand. A number of factors confirm this interpretation. The fact that no marine or marginal marine fossils were observed in the sand sequence or in strata above or below the sand suggest that deposition occurred inland, away from direct marine influence. The absence of glauconite is another factor pointing toward a fluvial origin for the sand. Finally, the stratigraphic position of the sand sequence, in reference to the large volume of sediments within the Denver basin, places it in an area where fluvial deposits have prograded out and over deltaic and marine sediments.

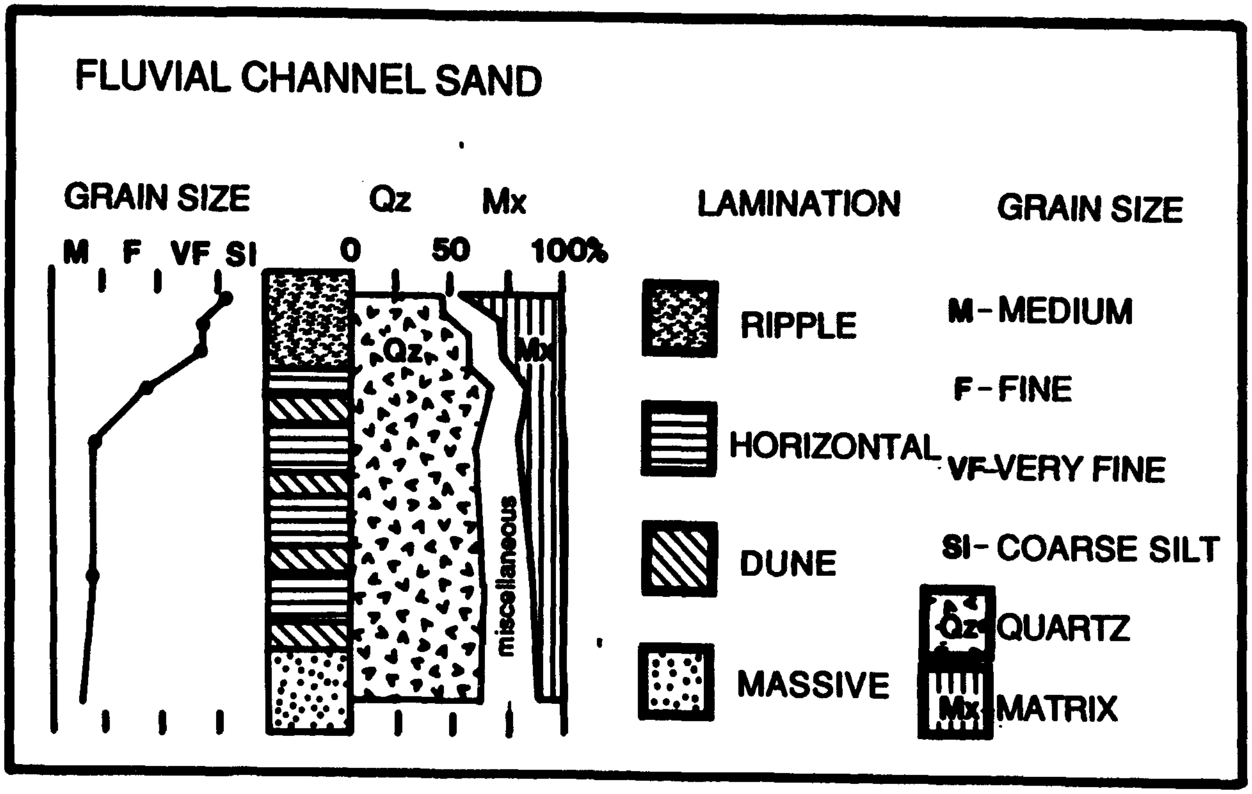

Figure 38. Diagnostic characteristics of a fluvial channel (after Berg 1986)

5 Supplementary Case Study

As discussed in the Case Study section there were a few problems encountered in applying the rationale for exploration to the case study at the Rocky Mountain Arsenal. This section addresses one of those problems, that of insufficient data locations of the depth needed to encounter the Arsenal "target" sand.

To alleviate this problem, another site was selected. This "supplementary" site was chosen from a modern day stream. A modern stream allowed for a close to absolute definition of a sand body, for comparison of what is visibly defined with that which is defined by the rationale for exploration.

Site Description

The site chosen for this supplemental application of the rationale for exploration is a portion of the Brazos River floodplain in central Texas. The general location is shown in Figure 39. Availability of satellite imagery and a corresponding topographic map dictated the choice of the Brazos River.

Satellite imagery and a U.S. Geological Survey topographic map of the same area, the Austin, Texas 1:250,000 scale map, were used to obtain approximate floodplain boundaries. These floodplain boundaries subsequently were assumed to represent the width of the stream's sand body. The site is a 275,000 ft east to west and 225,000 ft north to south area, bounded by the central Texas state grid coordinate system lines of 3,100,000 ft and 3,275,000 ft East, and 275,000 ft and 500,000 ft North. It encompasses the Brazos River from just west of Hearne, Texas to near where the Navasota River joins the Brazos River at Navasota, Texas. Figure 40 shows the site boundaries and the Brazos River floodplain boundaries.

From measuring the width of the Brazos River floodplain boundaries, the sand body width was mapped to be approximately 24,000 ft. From this width, a sand body thickness of approximately 80 ft was back calculated from Lorenz's and Leeder's equations (described in Rationale for Exploration section). This 80 ft thickness was assumed to be uniform for any location within the sand body. Thus both a thickness and boundary for the hypothetical sand body were obtainable for any location in the site.

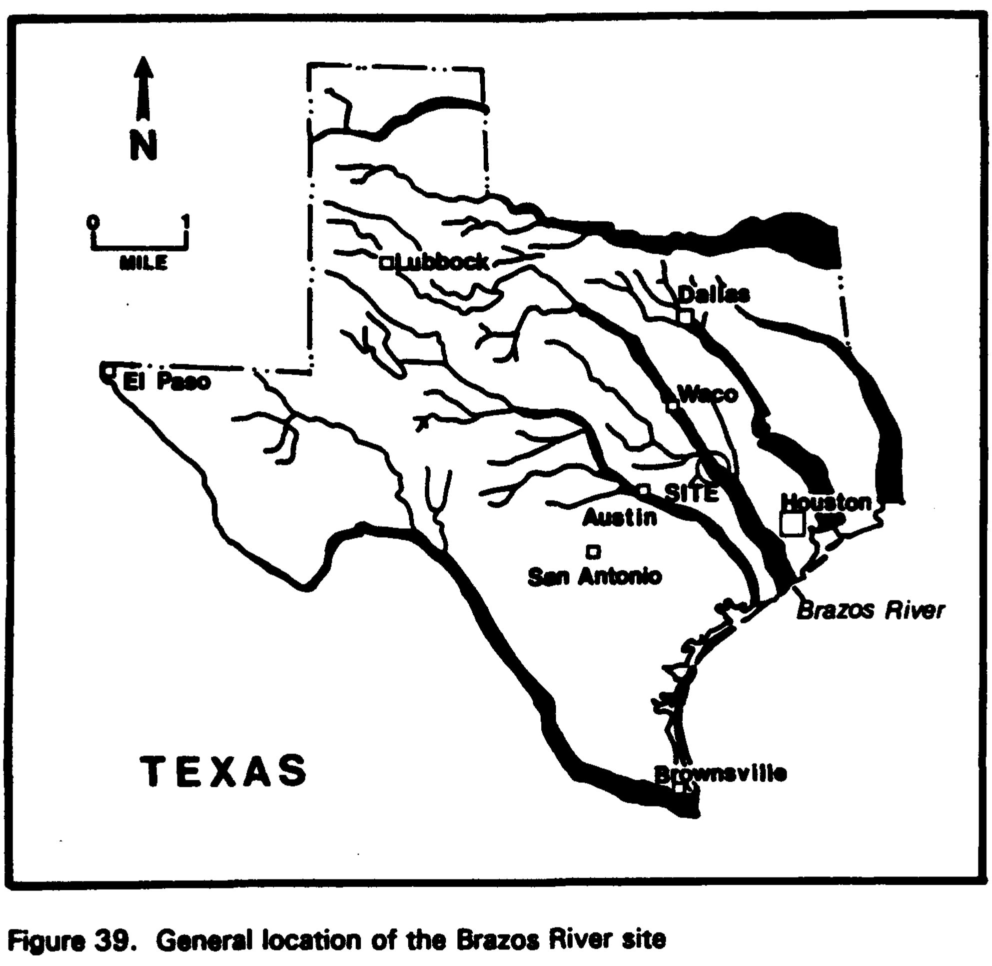

Figure 39. General location of the Brazos River site

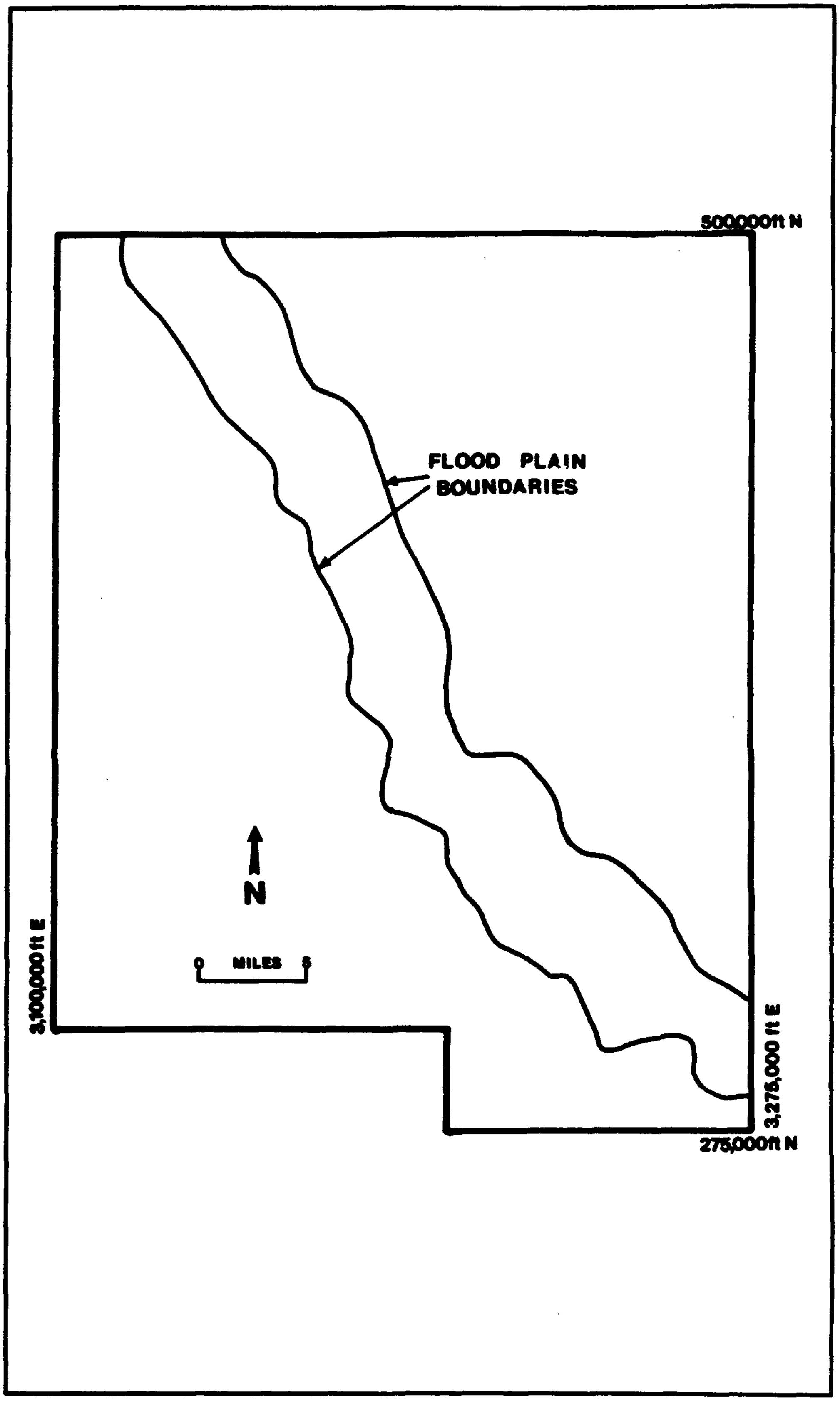

Figure 40. Brazos River site and floodplain boundaries

Application of the Rationale for Exploration

With the assumptions described above, the rationale for exploration was applied to the site. Thus, any location selected by this rationale provided the needed information, and the process could continue for any level of information desired.

The boundary of the site was hypothetically drilled with 25,000 ft spacing between boring locations. The spacing was chosen somewhat arbitrarily, although this spacing could have been hypothetically based on encountering sand body width(s) of concern, such as that of the Brazos River. These are shown in Figure 41. Figure 41 also shows which locations encountered the assumed 80 ft thick sand body. Even though the sand would have been encountered early in the hypothetical drilling, the boundary was completely drilled, as would be the case in most environmental applications.

The hypothetical sand body was then followed through the site from the southern most boring location which intersected the sand body. Again, environmentally, this would be an exit point for any pollutant, so the down gradient and thus potential exit point would need to be defined first.

Since the boundary had been hypothetically drilled, several data points existed. These were used to produce contours of the standard deviation of the thickness estimates obtained from kriging with the Geo-EAS program, in the same manor as described previously in the Case Study section. These standard deviations are shown in Figure 42.

From the curves in Figure 5, the interval for data point, or hypothetical boring, spacing of approximately 17,500 ft was obtained. This is the spacing for a 50 percent probability of dual penetration of a 24,000 ft wide sand body in order to define the sand body.

This distance, of 24,000 ft from the boring which encountered the hypothetical sand, was in a area where the sand thickness standard deviation was less than the standard deviation of the whole data set. One boring was hypothetically placed where the highest standard deviation occurred at that distance, as shown in Figure 43.

Often during the hypothetical exploration, the boring spacing would not be enough to place an additional boring out of the area where the sand thickness standard deviations were less than the standard deviation of the whole data set. When this happened, usually only one additional boring was placed where the higher standard deviation would occur. Only in a couple of instances were two borings chosen at the same time due to a large enough area (regarding the boring spacing) with the same standard deviation.

This procedure was followed during the hypothetical exploration through the site, defining the sand. The fifteenth boring that was added after the boundary borings, produced estimates of the sand thicknesses whose standard

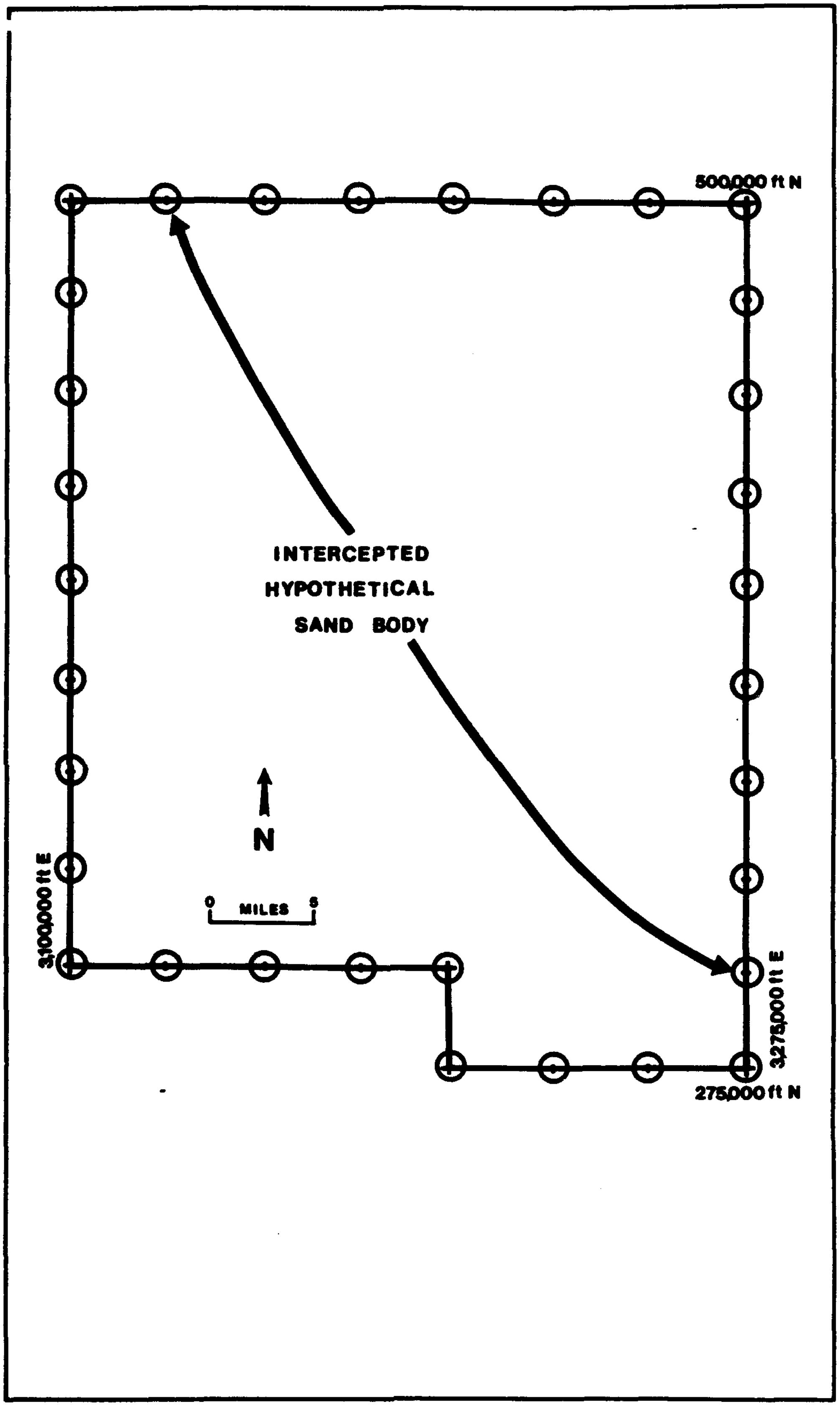

Figure 41. Brazos River boundary for boring locations

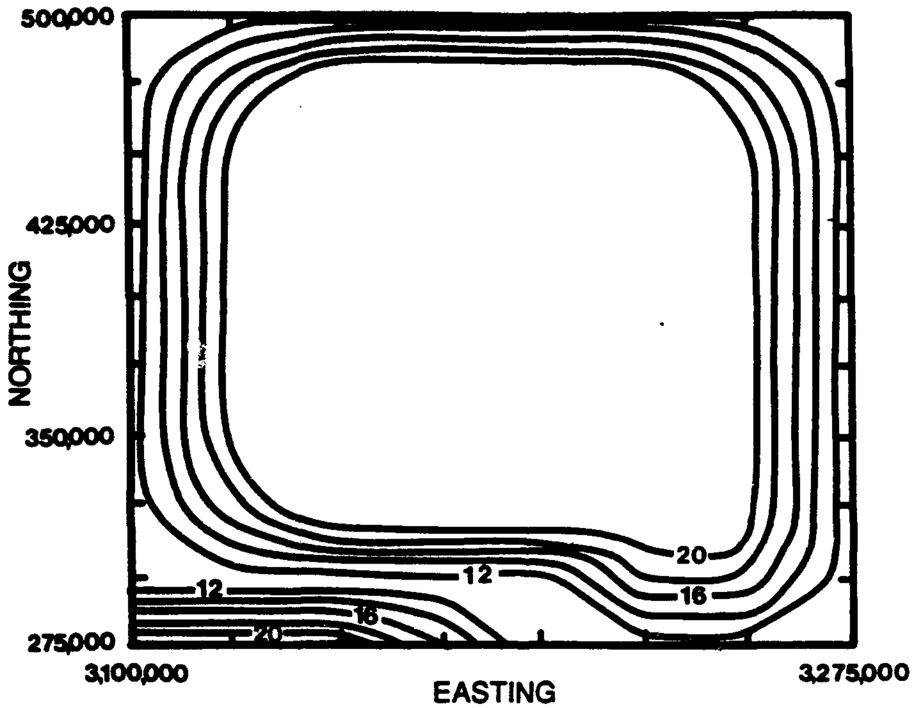

Figure 42. Standard deviation, in feet, for the Brazos River boundary data

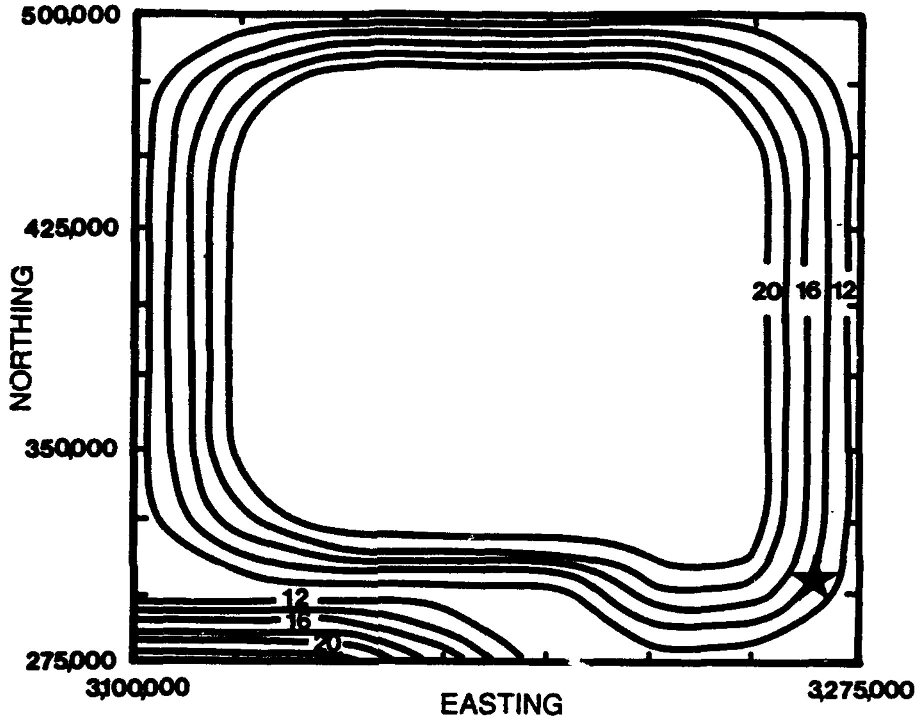

Figure 43. First definition boring location

deviations were less than that of the whole data set. This was determined by the contoured thickness estimates, compared to the contoured standard deviation of those thicknesses. This was done for the area in which the estimated sand body thicknesses occurred.

The proximity of the first of the definition borings to the south and east site boundary borings coincidentally guided the first boring locations in the direction of the sand, and provided low enough standard deviations so that no borings were needed outside the sand body. As the borings moved further into the site, the procedures resulted in the highest sand thickness standard deviation and occasionally the standard deviation which was greater than the standard deviation of the whole data set to occur in the direction of the sand body. When the procedures took the location of a boring out of the sand body, the next location would be chosen in a direction that resulted in intersecting the sand body again, always with the 17,500 ft spacing and in the direction of the highest standard deviation.

On two occasions, the results of a boring location placement resulted in sand thickness estimates whose standard deviations were less than the standard deviation of the whole data set and were uniform surrounding it. In these instances the next boring location was chosen in the direction of the northern boundary boring which encountered the sand. Had there not been another boundary boring that had encountered the sand body, three borings with equal, 17,500 ft, spacing from one another would have had to have been drilled to continue the exploration.

The definition of the sand body was considered complete once the standard deviations of the sand thicknesses were less than the standard deviation of the whole data set. This occurred after the fifteenth boring. However, four more boring locations were chosen at locations with relatively higher standard deviations in order to achieve relatively uniform standard deviation for the area containing the sand body. All nineteen boring locations are shown in Figure 44.

Appendix K contains the contoured standard deviations and each data point location as it was selected, in the order in which the hypothetical exploration proceeded. The standard deviation for each of the data sets is contained in Table 8. Each data set contains all the previous borings plus the one(s) added at each step, as described in the Rock Mountain Arsenal test case.

Application of the Grid Method for Exploration

The hypothetical sand body was also defined by grid drilling for comparison purposes. The spacing was kept the same as the original boundary borings (25,000 ft). The locations of these borings are shown in Figure 45. A total of thirty-four borings, in addition to the boundary borings, would have been drilled in the site containing the sand body using the typical grid method

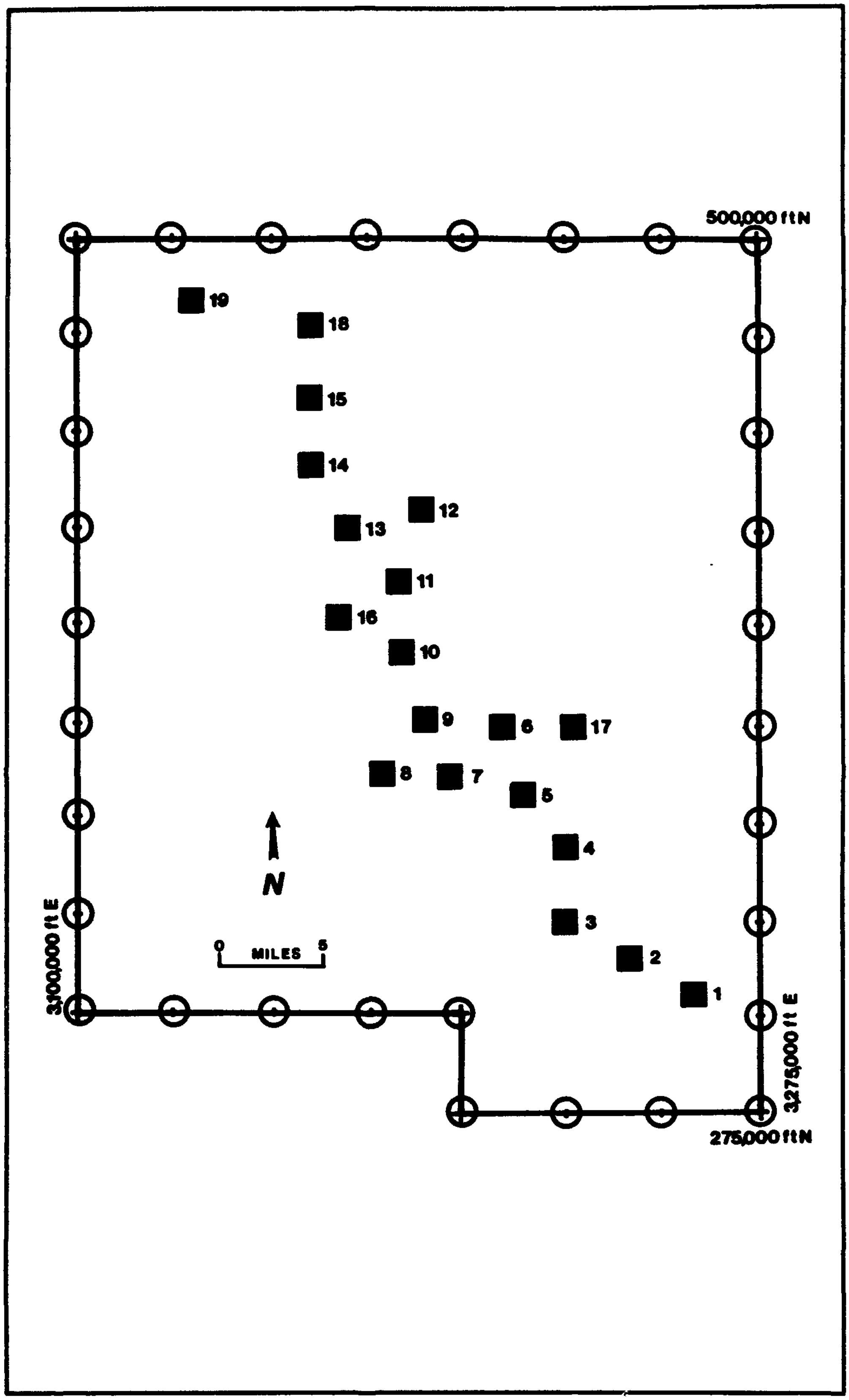

Figure 44. Boring locations added to define the hypothetical sand body by the rationale for exploration method, included are the boundary borings

Table 8
Data Set Population Standard Deviations for the Brazos River

Boring Population	Variance	Standard Deviation
Boundary Borings	375.00	19.3
Set 1	528.93	23.0
Set 2	664.36	25.8
Set 3	783.67	28.0
Set 4	888.89	29.8
Set 5	981.74	31.3
Set 6	1,043.50	32.3
Set 7	1,024.00	32.0
Set 8	1,096.50	33.1
Set 9	1,161.00	34.1
Set 10	1,218.40	34.9
Set 11	1,200.00	34.6
Set 12	1,251.60	35.4
Set 13	1,297.50	36.0
Set 14	1,338.50	36.6
Set 15	1,306.10	36.1
Final Set	1,328.70	36.4

for exploration. This was twenty-five more borings than required by the rational for exploration.

Had geology been taken into account in this typical grid method during the exploration, and limited the number of borings to those just outside of the sand body, as shown in Figure 46, twenty-five borings, in addition to the boundary borings, would have been necessary to define the sand body. This is still ten more than required by the rational for exploration, to define the sand body reliably.

This data set was kriged to obtain estimated thicknesses and standard deviations of those estimates for comparison with those obtained by following the rationale for exploration. This would not normally be done in a gridding type of exploration program.

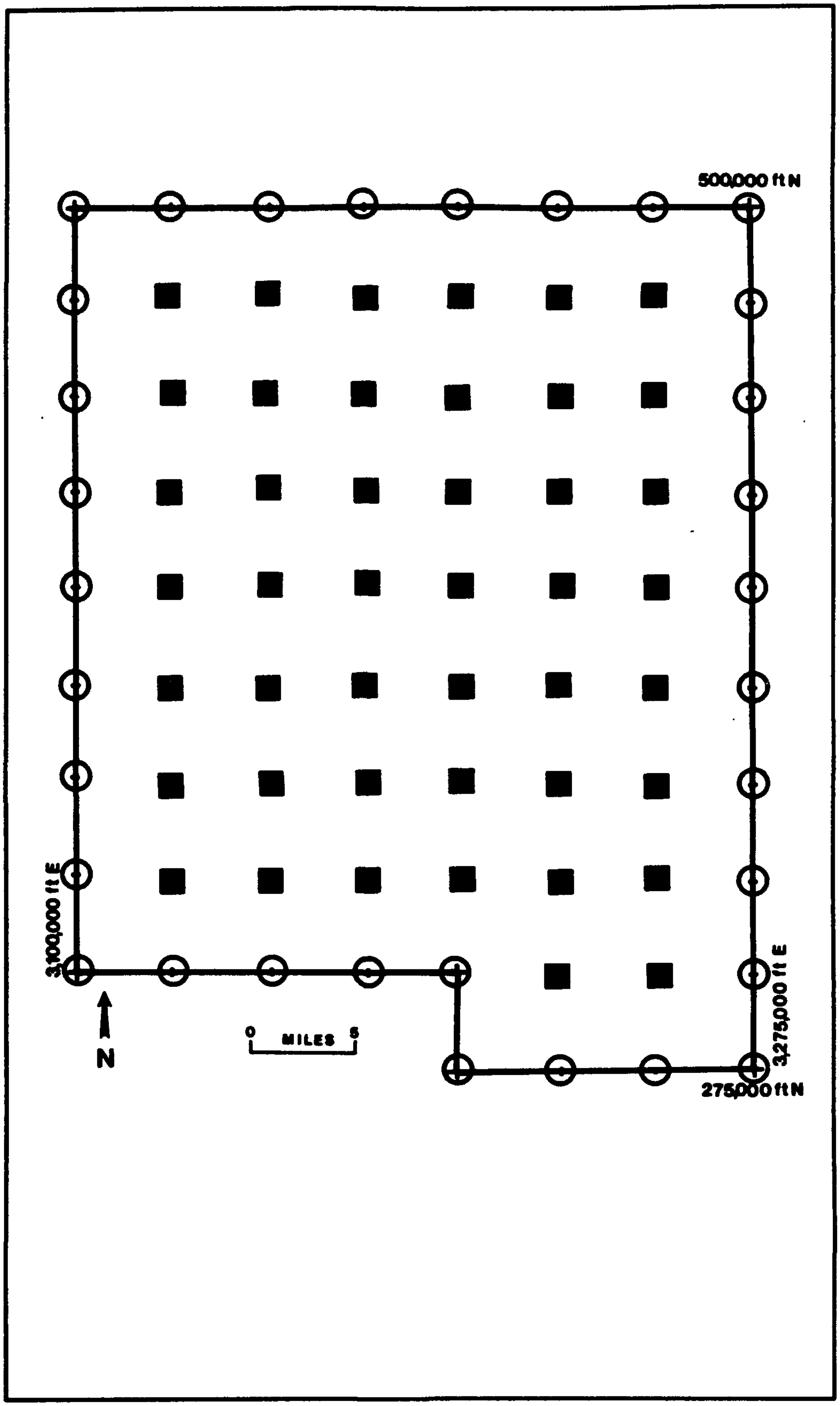

Figure 45. Boring locations from a typical grid exploration method

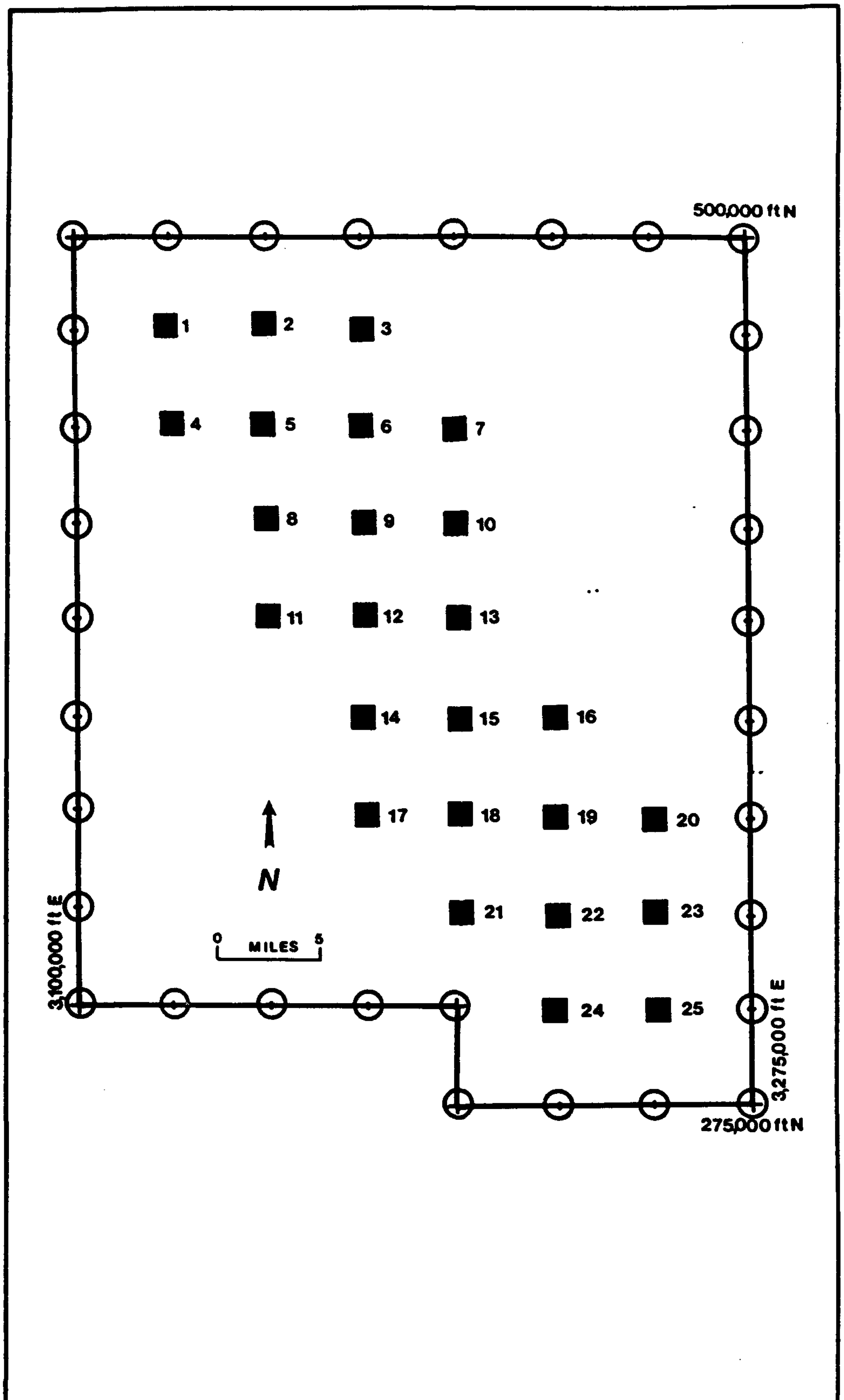

Figure 46. Boring locations defining the hypothetical sand body by a typical grid exploration method, included are the boundary borings

Comparison of Methods

Several parameters from the gridding method for exploration were compared to their counterparts obtained from the rationale for exploration method. These included the appearance of the estimated thicknesses produced by kriging, the number and spacing of boring locations needed by each to define the sand body, and the confidence statements for selected locations within the sand body.

The rationale for exploration method predicted the sand body with uniform sand thickness standard deviations from nineteen borings in addition to the boundary drilling. The gridding method for exploration required twenty-five borings to define the sand body. The gridding method also provided results in which the sand thickness standard deviations were less than the standard deviation of the whole data set, but kriging is not normally done for this method. The rationale for exploration boring spacing was 17,500 ft while the grid method boring spacing was larger, at 25,000 ft. Even more boring locations would have been necessary for the grid method to define the sand body with a spacing of 17,500 ft.

The sand thickness estimates of both methods are very similar, as shown in Figures 47 and 48. The standard deviation of the estimated thicknesses of the grid method are slightly lower than those from the rationale for exploration. The standard deviations for each method are shown in Figures 49 and 50. The slightly lower standard deviations for the grid method leads to slightly better confidence statements. However, the difference in directly comparable locations (the same thicknesses) is only a few feet. The locations for these confidence statements are shown in Figures 51 and 52. The confidence statements are contained in Table 9.

Estimated thicknesses were also obtained from data of the entire site on a 10,000 ft grid spacing, which was used to produce a variogram for the site. The locations of these data points are shown in Figure 53. Discussion relating to the variogram will be contained in the Geostatistics section. The standard deviation for this grid was uniform, thus, no contours were possible. However, the estimated thickness from this data set closely approximated the hypothetical sand body's geometry. These estimated thicknesses are shown in Figure 54.

The sand body's appearance from the estimated thicknesses from both methods of exploration are noticeably wider than that of this large data set. This is due to the differences in data point spacing, as well as the number of data points used. Obtaining such a large number of data points obviously adds to the definition and confidence, but is not reasonable, for reasons described in the Introduction section.

This large data set was useful in looking at the confidence statement locations. Confidence statements from locations corresponding to the edge of the sand body, which is shown in Figure 55, are shown for both methods in

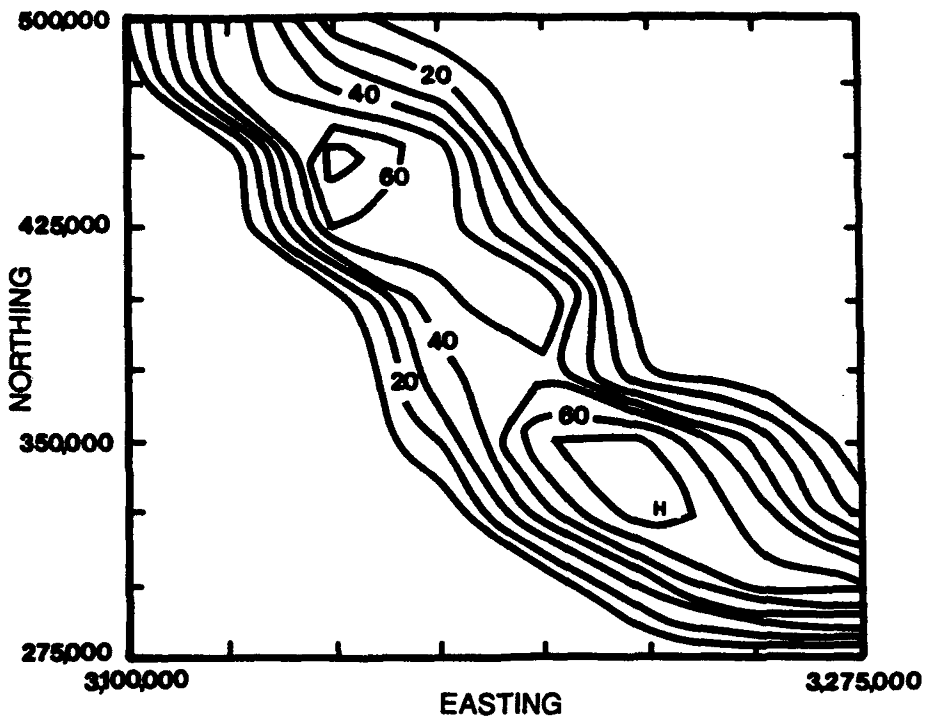

Figure 47. Estimated sand thickness, in feet, from the rationale for exploration method

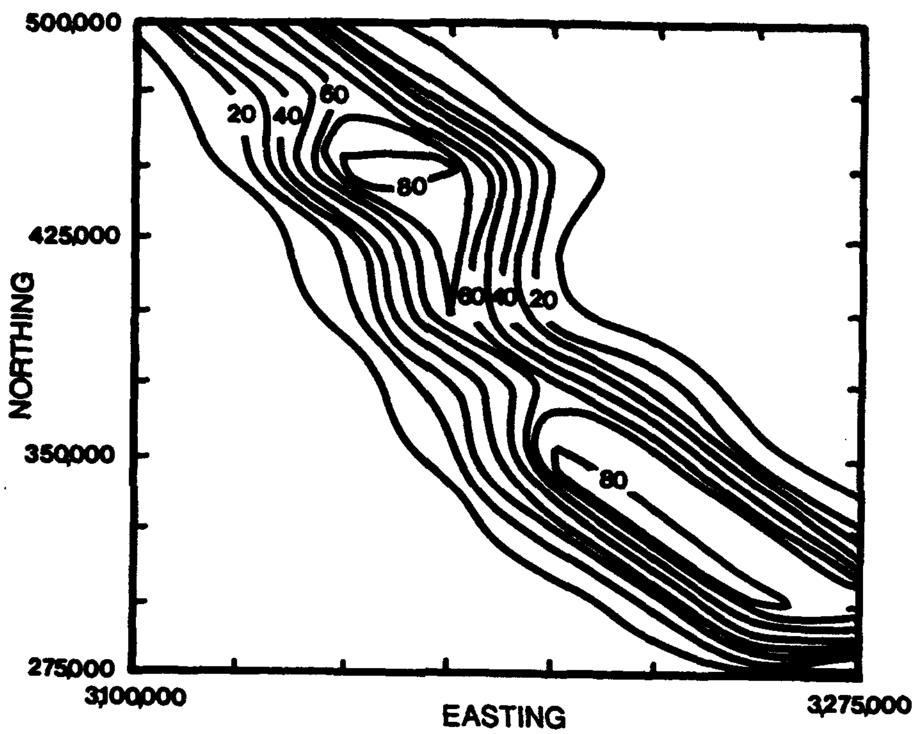

Figure 48. Estimated sand thickness, in feet, from a typical grid exploration method

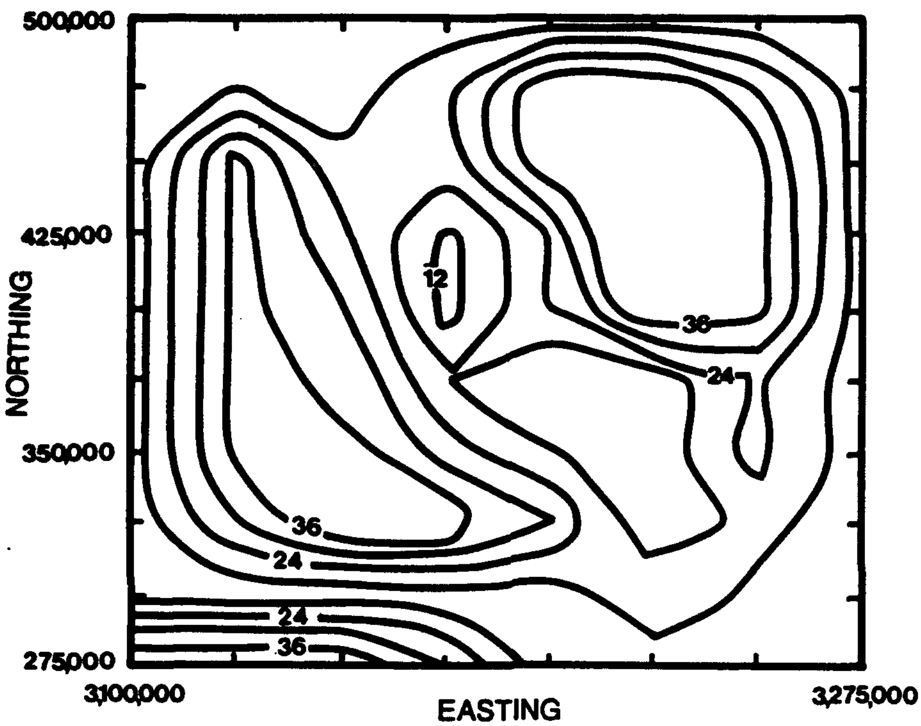

Figure 49. Standard deviation, in feet, for estimated sand thickness from the rationale for exploration method

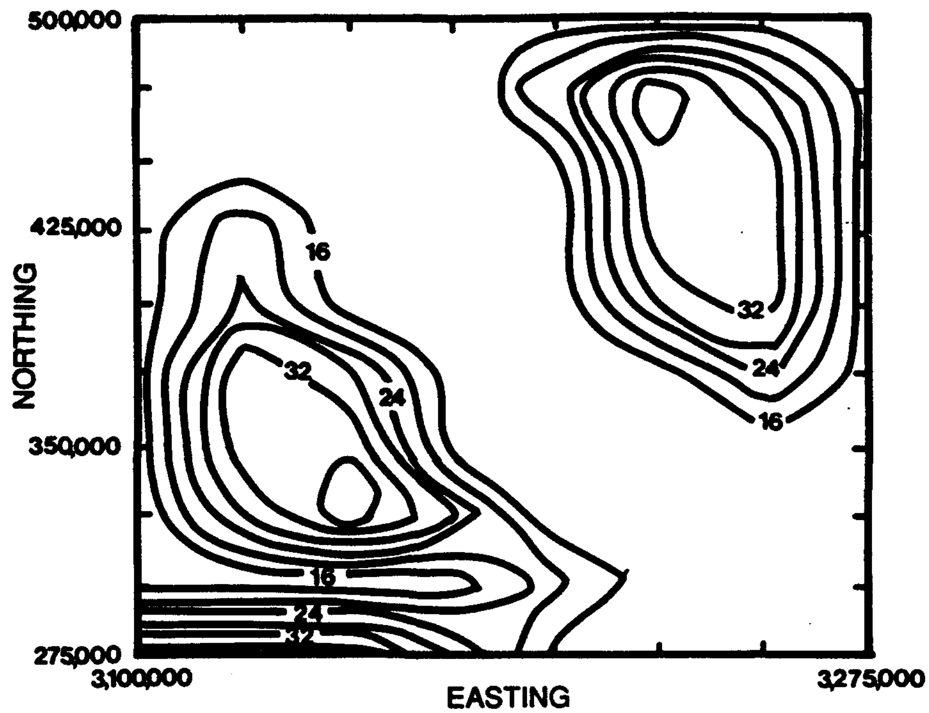

Figure 50. Standard deviation, in feet, for estimated sand thickness from a typical grid method of exploration

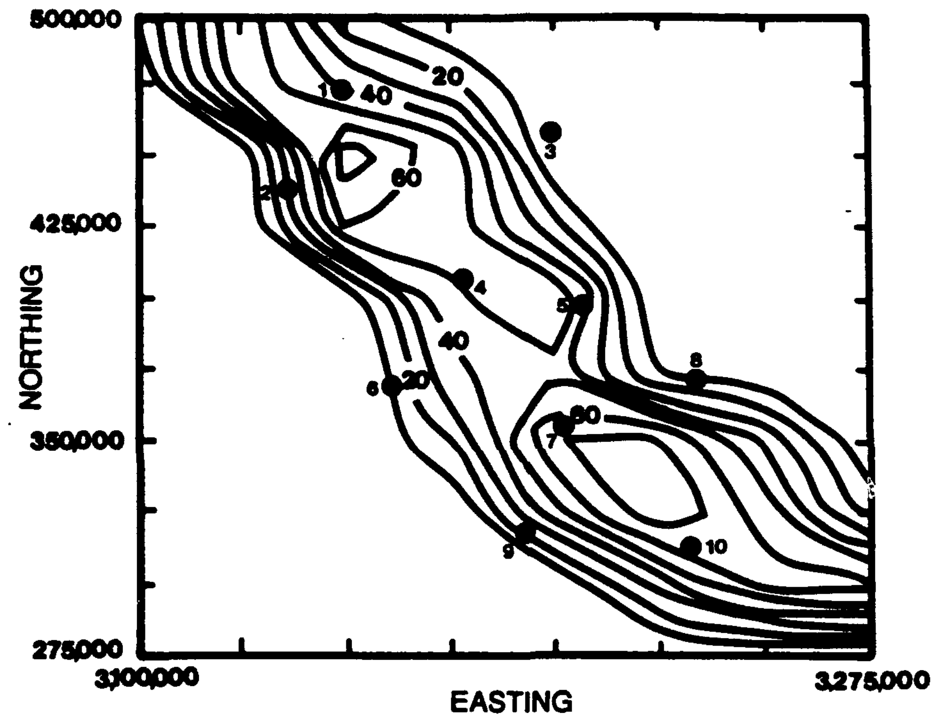

Figure 51. Locations of confidence statements in Table 9 for the rationale for exploration method

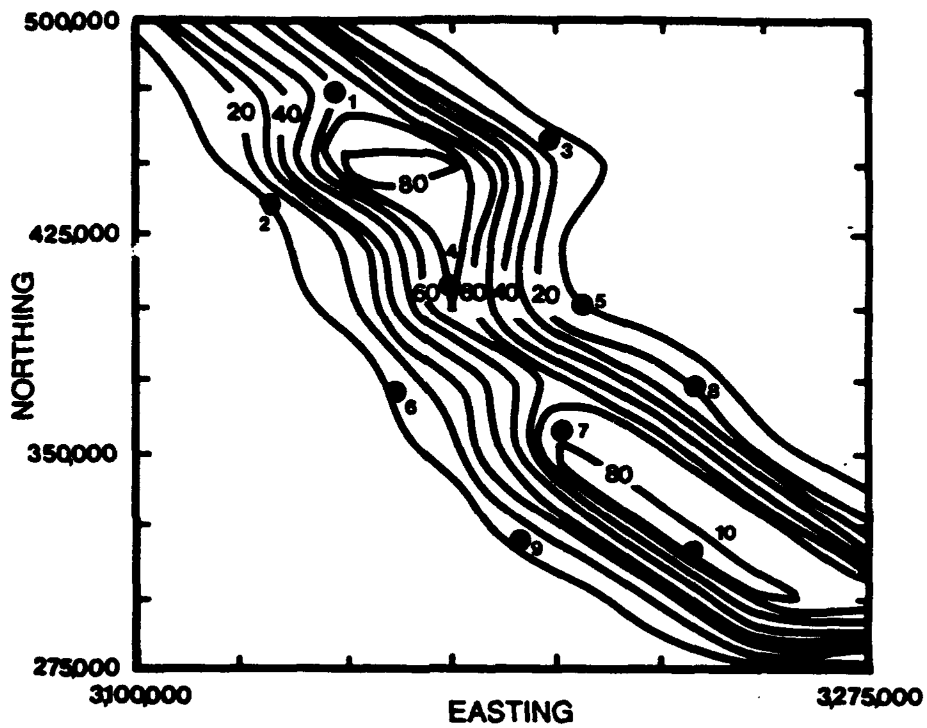

Figure 52. Locations of confidence statements in Table 9 for a typical grid exploration method

Table 9 Confidence Statements for Brazos River Locations Shown in Figures 51 and 52		
Location	**Grid Method**	**Rationale for Exploration Method**
1	60 ± <16	40 ± <18
2	10 ± 16	25 ± 32
3	15 ± 18	<10 ± >36
4	70 ± <16	50 ± 12
5	10 ± 16	45 ± 27
6	10 ± 22	10 ± 28
7	80 ± <16	55 ± 18
8	20 ± 16	10 ± 18
9	10 ± 20	20 ± 30
10	70 ± <16	60 ± 19

Table 10. Figures 56 and 57 show the locations where the confidence statements were obtained with respect to each method's estimated sand body thicknesses. This comparison shows that in the area where the close approximation shows 10 ft thicknesses, both cases show at least 20 ft thicknesses and greater. Assuming that the error is negative in each confidence statement gives estimates that are relatively closer to that of the close approximation, with some exceptions. The exceptions were the rationale for exploration confidence thicknesses which were noticeably higher. This results from the comparison locations picked. By viewing the estimated thicknesses for each method, changing the locations for confidence statements could cause the grid method to have noticeably high estimates of thickness and the rationale for exploration estimates of thickness to all be relatively close.

In both methods, the thicknesses are noticeably over-estimated near the close approximation sand boundary. However, both methods indicate that at those boundary locations the sand body was present. In other words, the thickness estimate is larger than the possible error. Some of the locations from Figures 51 and 52 show a potentially negative error that if subtracted from the estimated thickness would result in a negative estimate. In these cases it cannot be said for sure that the sand body exists at that location. From this data it appears that if the negative error is taken and subtracted from the estimated thickness, the sand body boundary is approximated by resulting numbers approaching 0, but not becoming negative.

As stated earlier, better confidence can be established by increasing data point locations. However, the objective is to define the sand body with the least number of data points. The traditional grid method yielded similar results, in estimated sand thickness and standard deviations of those estimates, to those produced by the rationale for exploration. With the rationale for

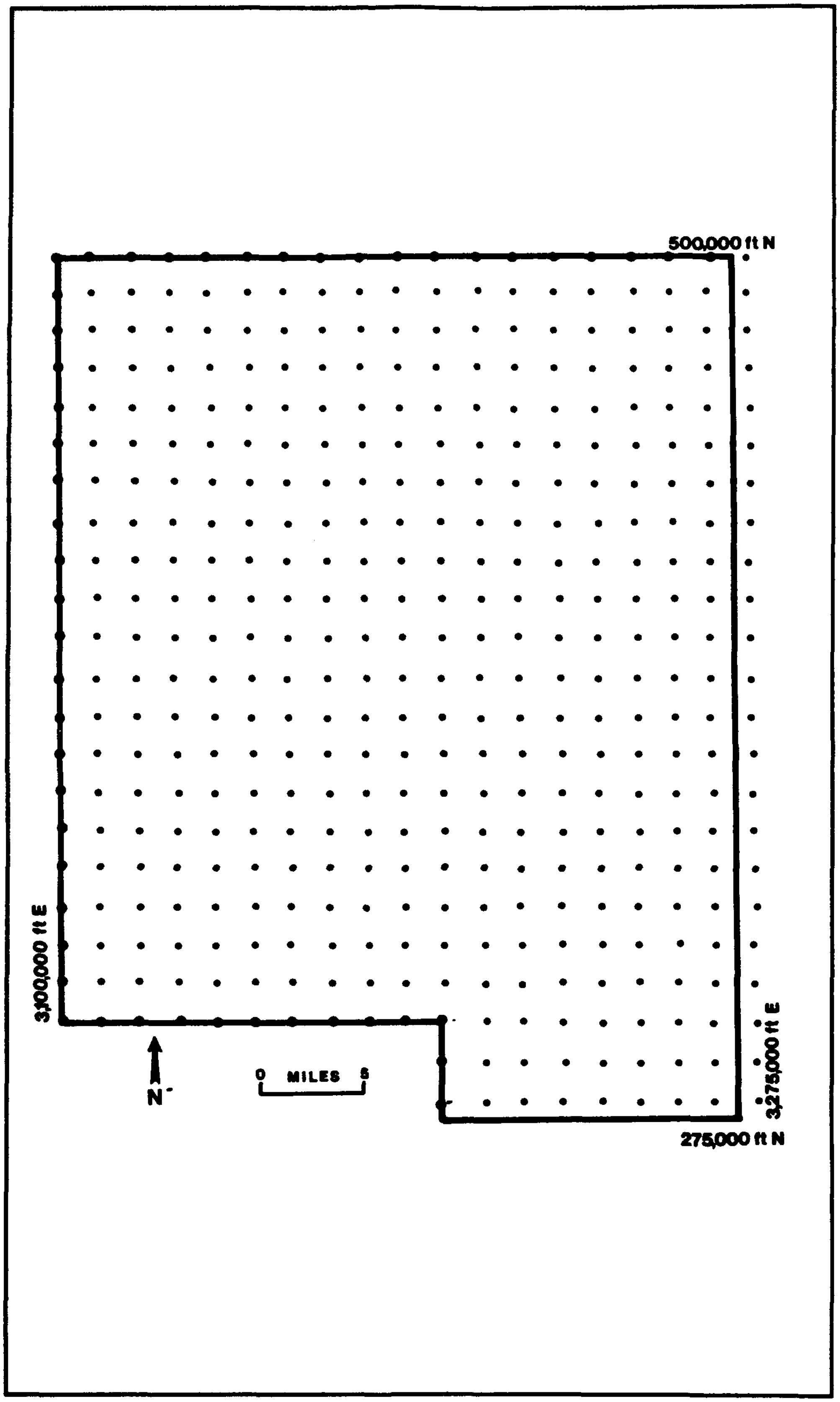

Figure 53. Data point locations for the Brazos River 10,000 foot grid

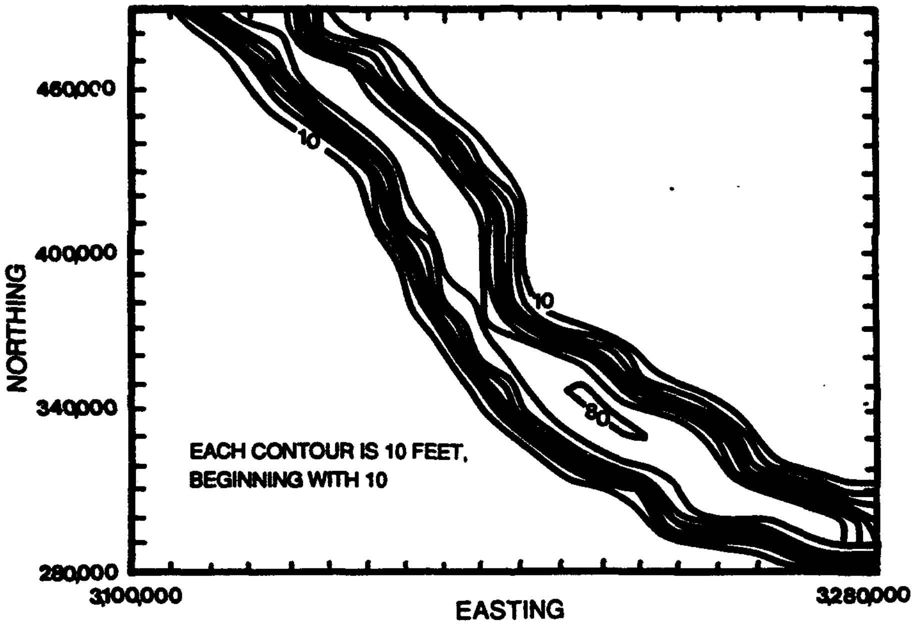

Figure 54. Estimated sand thickness, in feet, from the Brazos River 10,000 foot grid

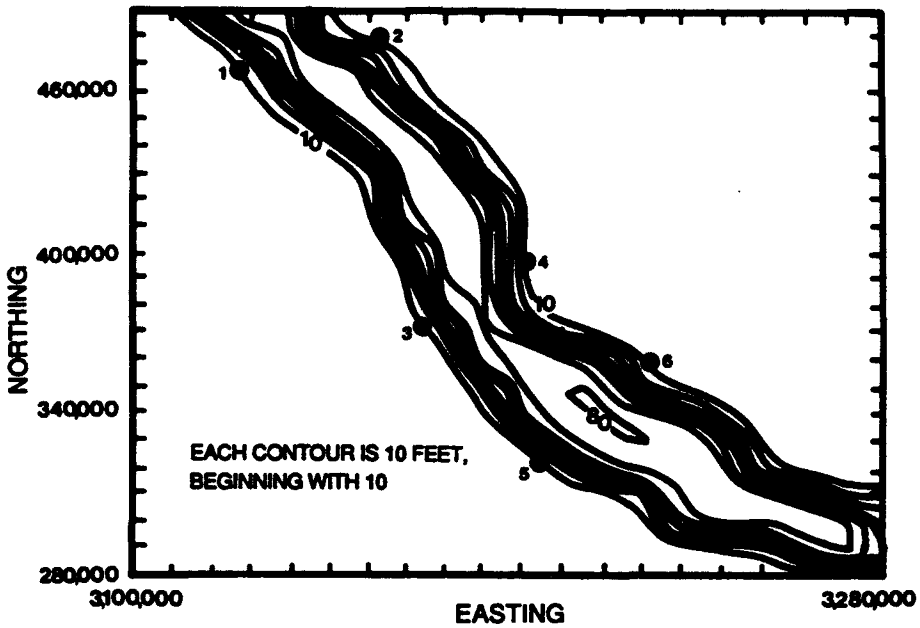

Figure 55. Locations chosen for the confidence statements in Table 10

Table 10
Confidence Statements (in ft) for Brazos River Locations Shown in Figures 55, 56, and 57

Explanation	Location					
	1	2	3	4	5	6
Grid Method 95 percent Confidence	30 ± <16	20 ± <16	25 ± 16	20 ± <16	30 ± 16	35 ± <16
Error Subtracted	<14	<4	9	<4	14	<19
Rationale for Exploration 95 percent Confidence	>50 ± 18	20 ± <18	20 ± 21	55 ± 21	45 ± 30	30 ± 16
Error Subtracted	32	<2	-1	34	15	14

exploration requiring fewer data point locations, then the definition of the sand body with the least number of data points was accomplished by the rationale for exploration.

Also important is that the sand body could be followed through the site as in the Case Study section. This is particularly useful for some applications, such as oil and gas exploration. Table 11 contains a summary of the comparison of the definition of the sand body by the traditional grid method and by the method described by the rationale for exploration.

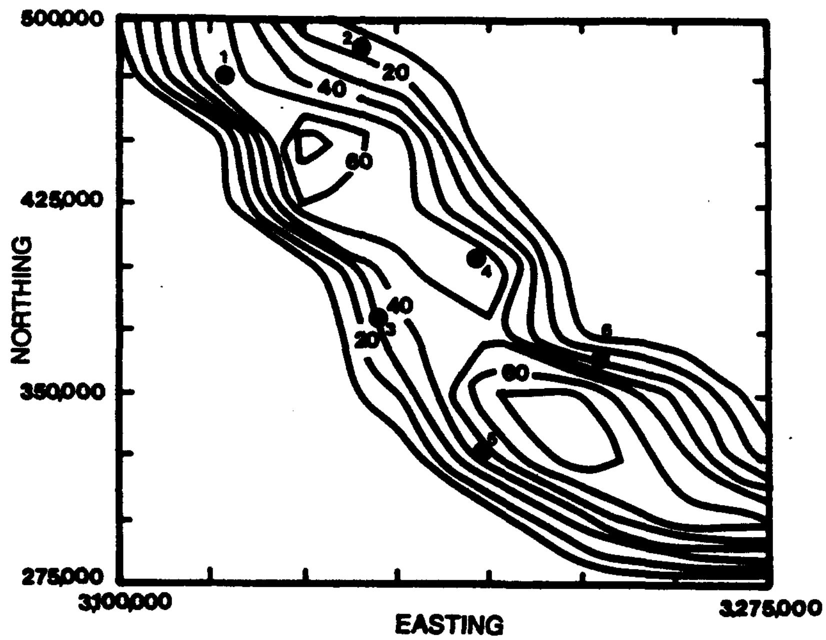

Figure 56. Locations of confidence statements in Table 10 for the rationale for exploration method

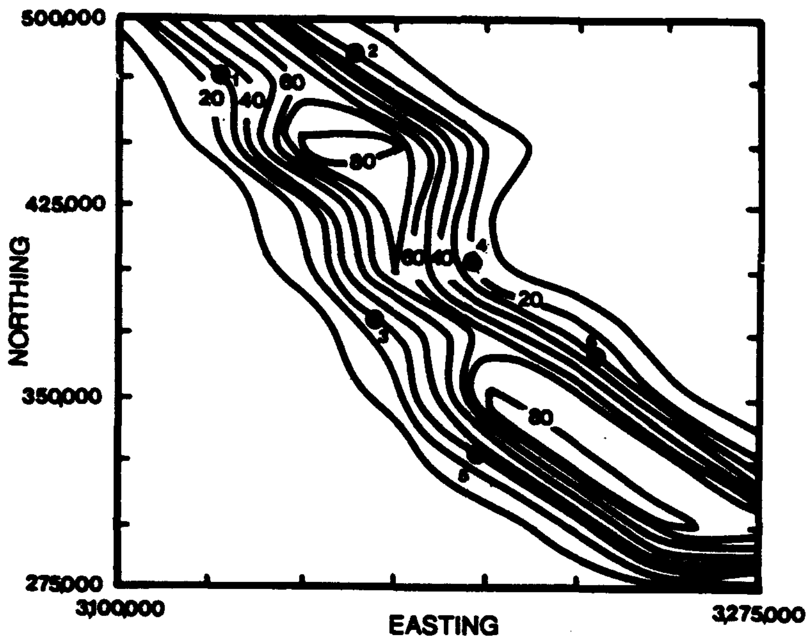

Figure 57. Locations of confidence statements in Table 10 for a typical grid exploration method

Table 11
Summary of Comparison for Selected Parameters of Different Exploration Methods

Parameter Compared	Grid Method	Rationale for Exploration Method
Grid spacing	25,000 ft	17,500 ft (based on sand body width)
Number of definition borings	25	15 (reliably)
Thickness estimates compared to those of 10,000 ft grid	Higher	Higher (slightly higher than those of the grid method)

6 Geostatistics

A statistical method was chosen to produce estimates of sand thickness and subsequently errors for those thicknesses. The method chosen, which has already been named in earlier sections, was kriging. Specifically, ordinary block kriging was used.

Kriging is a form of weighted local averaging. Kriging is considered optimal for geologic data sets by numerous authors (Davis 1986, David 1977, Clark 1979, etc.). This is because the method provides estimates of values at unrecorded places without bias and with minimum and known variance, provided there is a model for the semi-variogram. Kriging produces those estimates with a lower number of observations than that of conventional methods. Clark (1979) gave the points of major importance found in numerous publications as: (1) Given the basic assumptions, no trend, and a model for the semi-variogram, kriging always produces the best linear unbiased estimator. (2) If the proper models are used for the semi-variogram, and the system is set up correctly, there is always a unique solution to the kriging system. (3) If you try to estimate the value at a location which has been sampled, the kriging system will return the sample value as the estimator, and a kriging variance of zero. In other words, you already know that value. This is usually referred to as an exact interpolator. (4) If you have regular sampling, and hence the same sampling/block setup at many different positions within the deposit, it is not necessary to recalculate the kriging system each time. Figure 58 shows results of Di et al.'s (1989) comparison of a conventional method to the kriging method and that the kriging method produced lower standard errors. Conventional methods include standard errors of the mean, student's t test, least squares analyses, analysis of variance, etc. The above descriptions served as the basis for selecting kriging for this application.

The semi-variogram, also termed simply the variogram, is a curve of the variation of a numeric variable, thickness in this application, versus distance between pairs of known, or control, points. Estimates of the semi-variogram are used to determine the weights applied to the data when computing the averages and are presented in the kriging equations.

Since kriging is an advanced technique involving intense computing, it must be done with a computer. For this application, as mentioned in a previous section, a public domain program was used. This program which is

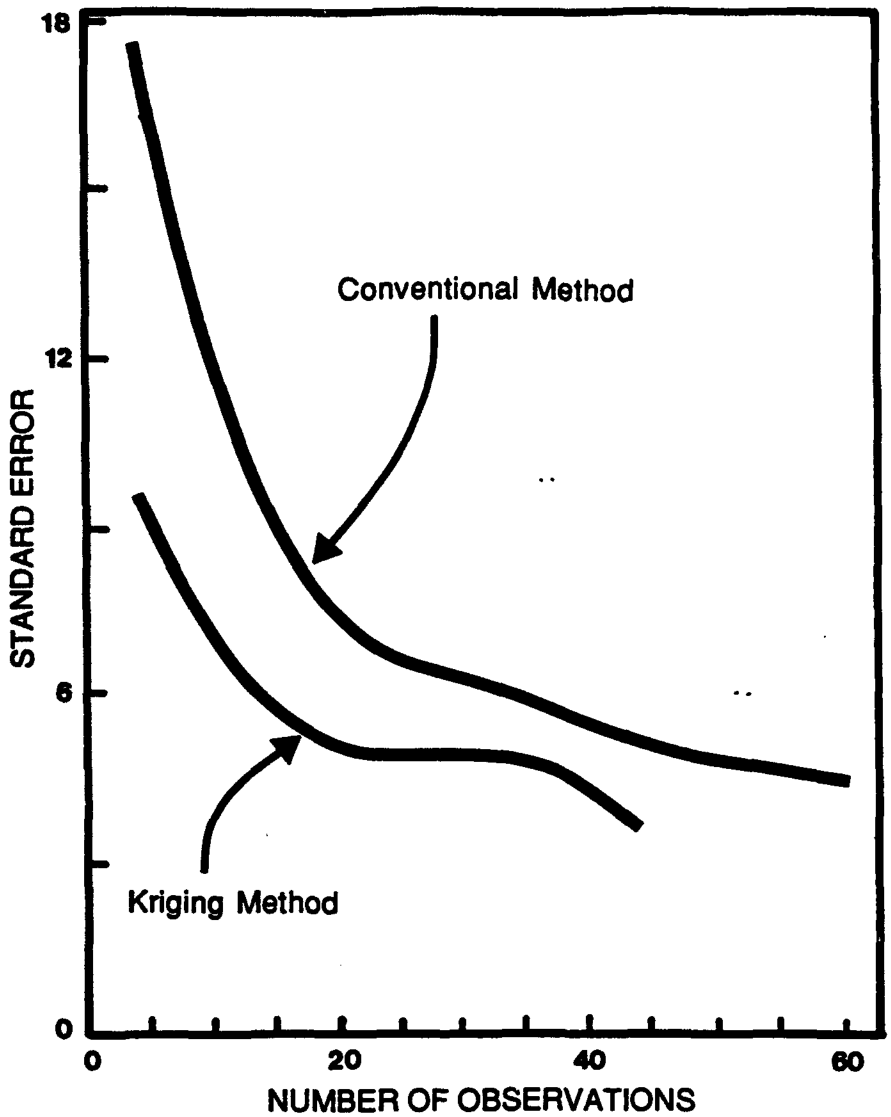

Figure 58. Di and others' comparison of conventional method to the kriging method (after Di et al. 1989)

called Geo-EAS (Geochemical Environmental Assessment Software), was developed by the U.S. Environmental Protection Agency. This program contains sub-routines which allow for the generation of the variogram, kriging the variable values with the generated variogram, and contouring the output values. The kriging also produces standard deviation for the kriged values, which can be contoured.

Because the Geo-EAS program is public domain and contains all the desired routines in one package, it was used for the calculations of the kriging method and subsequent contouring. Also, if used in field application, speed of obtaining the needed locations is crucial, therefore a relatively easy to use program with all the needed products is desirable.

Obtaining the Variogram

There is disagreement in the geostatistical literature in using semi-variogram or variogram as the correct term. For this application, variogram will be used, for simplicity.

The variogram as defined by Englund and Sparks (1988) is a plot of the variance of paired sample measurements as a function of the distance between samples. Variograms provide a means of quantifying the commonly observed relationship that samples close together will tend to have more similar values than samples far apart.

The variogram is necessary for kriging, and is a critical part of this, as well as any geostatistical, study. The variogram is the interpretation of the spatial correlation structure of the sample data set. It controls the way that kriging weights are assigned to samples during interpolation, and consequently controls the quality of the results.

Englund and Sparks (1988) point out that all interpolation and contouring methods make the assumption that some type of spatial correlation is present, that is, they assume that a measurement at any point represents nearby locations better than locations farther away. Variogram analysis attempts to quantify this relationship. In other words, how well can a measurement be expected to represent another location a specific distance away? Experimental variograms plot the average difference of pairs of measurements, as one half the squared difference (variance), against the distances separating the pairs. If all possible sample locations were measured, a true variogram could be computed for the site where the variance of all pairs of measurements would satisfy each combination of distance and direction. Since, this is not usually possible, limited data is used to compute variances and then plot a graph of the variances versus distance. Then, a curve is fitted to the graph. This model is assumed to be an approximation of the true variogram.

Several types of variograms are possible. The Geo-EAS program allowed choices, so that each type could be compared. These were the ordinary

variogram, relative variogram, "mad'ogram", and the non-ergodic or Covariogram. Englund and Sparks (1988) describes each as follows. The relative variogram is analogous to the relative standard deviation often used to measure analytical variability. When modeled and used for kriging the relative kriging standard deviations must be multiplied by the estimated values to be comparable with kriging standard deviations produced with ordinary variogram models. The "mad'ogram" plots the mean absolute differences, but is not recommended for kriging. The non-ergodic or covariogram is based on estimates of covariance rather than variance. The covariograms have the same units as ordinary variograms and may be modeled and used for kriging in the same way. The covariance values, rather than variogram values, are actually used in the Geo-EAS kriging matrix equations for greater computational efficiency.

Once the type of variogram is selected, there are several mathematical models which may define the graph. Again, Geo-EAS allowed choices, so that each model could be compared. These are the spherical, exponential, linear, and Gaussian. The spherical model of the variogram is observed frequently in experimental data (Englund and Sparks 1988).

To fit any model to the variogram, an estimate of the Y-intercept, termed the nugget, is needed. The difference between the nugget and the maximum Y value, termed the sill, is also needed. Finally, the distance at which the model reaches the maximum value, termed the range, is needed. Although some form of least squares criteria could be used, the Geo-EAS program selection is subjective, picking the model by trial and error which gives the best fit.

The Geo-EAS program also allows for using data in a specified direction, or from all directions, to specify pair orientation criteria for the variogram computations.

As mentioned in the Case Study section, there was a problem in obtaining the variogram because of the limited amount of data used in those data sets. Although the covariogram with a spherical model in a specific direction appeared to be the best, it was questionable. In particular, the range was poorly defined. However, when kriging, the Geo-EAS program allowed for a minimum and maximum range so that an area could be bracketed for the range. Examples are the variograms produced from the Rocky Mountain Arsenal data set 1, shown in Figure 59 and from the Brazos River boundary data set, shown in Figure 60. The other variograms for the remainder of the data sets are contained in Appendix F.

To justify the type and model of variogram used for this application, and if it should be directional, larger data sets for the same variable, thickness, were used to generate more graphs. One data set contains all the data from the Rocky Mountain Arsenal that encountered the target sand, one contains all the data for a 10,000 ft grid for the Brazos River and another contains data from a 1000 ft grid for the Salt River in Phoenix, Arizona. The Salt River was added to the sites already used to reduce the chance of a coincidental

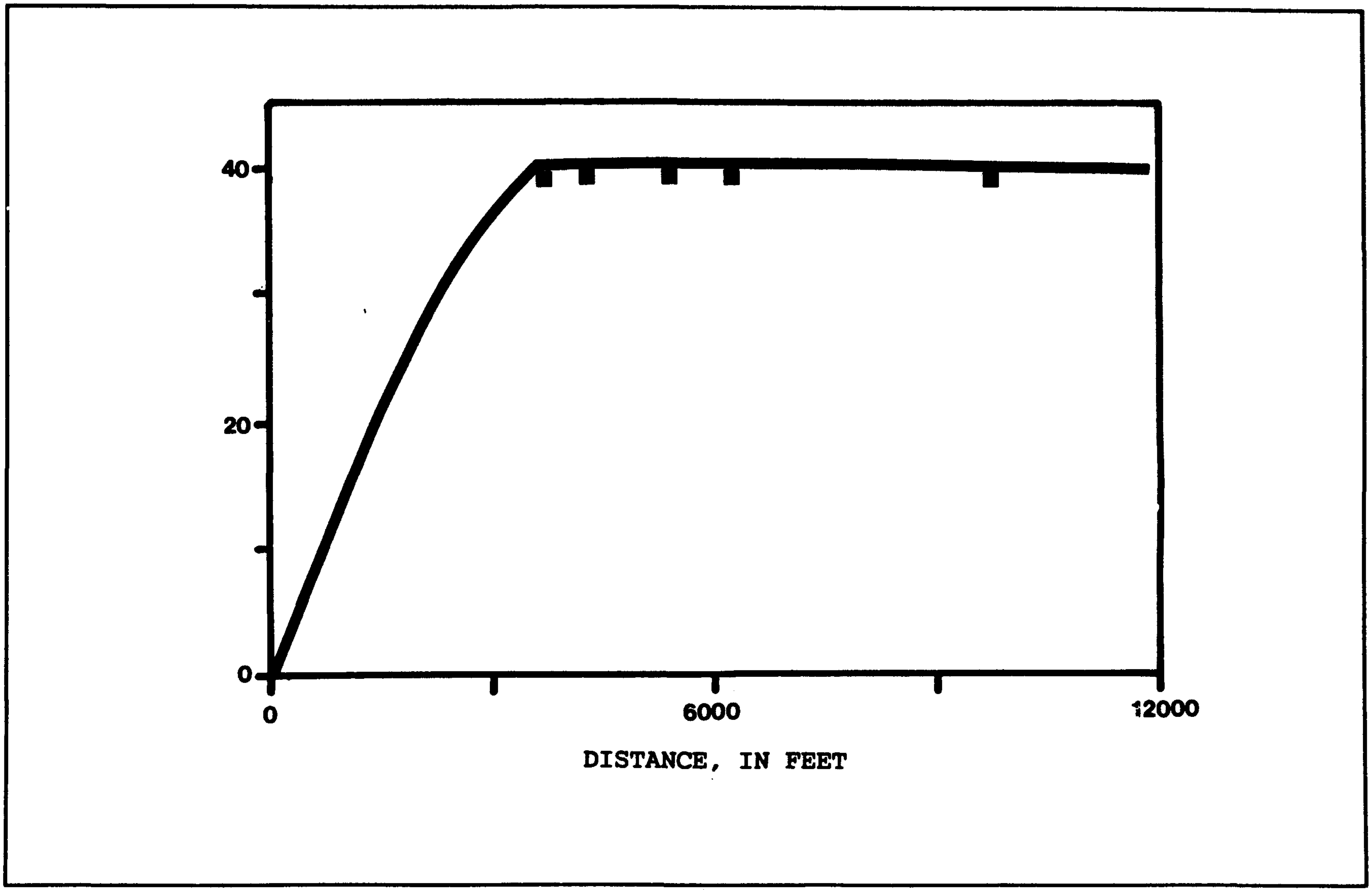

Figure 59. Variogram for Rocky Mountain Arsenal data set one (each plot may represent more than one data point)

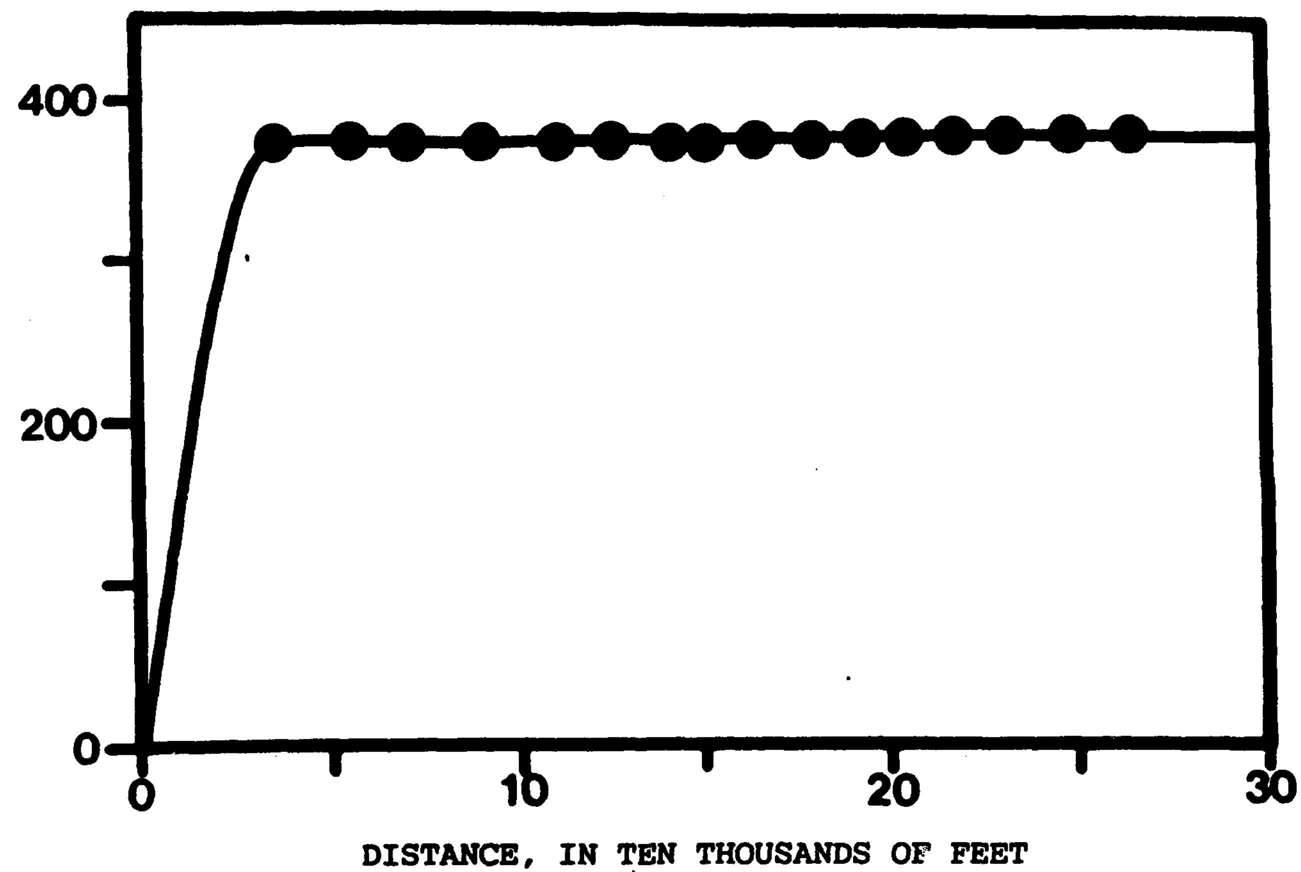

Figure 60. Variogram for Brazos River boundary data set (each plot may represent more than one data point

agreement between the type and model of variogram, and for additional variety of sand body size and climatic conditions. The sand width and thicknesses for the Salt River were obtained in the same manor as that of the Brazos River, described in the Supplemental Case Study section. Satellite imagery and the Phoenix, Arizona 7-1/2 min quadrangle were used in this case. The Salt River site is bounded by the Arizona state grid coordinates of 435,000 ft and 775,000 ft East and 875,000 ft and 884,000 ft North. The general location of the Salt River site is shown in Figure 61. Figures 26, 53, and 62 show the data point locations for each of these. Tabulation of the data is contained in Appendix E.

These data sites allowed for a variety in orientation through the site, size (width and thickness), climates, and ages of sand bodies. In each case, a directional covariogram with a spherical model was the best fit for the data. Therefore, the type and model of the variogram, which results from the data sets in the case studies, are justifiable. Figures 63, 64, and 65 show these variograms. Appendix F contains other variograms used in this project.

Kriging

As previously described, kriging is a weighted-moving-average interpolation method where the set of weights assigned to samples minimizes the estimation variance, which is computed as a function of the variogram model and locations of the samples relative to each other, and to the point or block being estimated (Englund and Sparks 1988).

As the above definition reveals, kriging estimates can be for an area, termed block, or for a point. Point kriging usually provides estimates similar to block kriging. However, if a point being estimated coincides with a sampled location, the estimate is set equal to the sample value. This is not appropriate for contour mapping, which implicitly requires a spatial estimator (Englund and Sparks 1988).

The kriging estimates can be produced with either ordinary or simple kriging. Ordinary kriging estimates the point or block values with a weighted average of the sample values within a local search neighborhood, centered on the point or block. Simple kriging also assigns a weight to the population mean, but makes a strong assumption that the mean value is constant over the site. It also requires that the available data be adequate to provide a good estimate of the mean (Englund and Sparks 1988).

The kriging portion of the Geo-EAS program allows for a selection from these choices. From the above statements, the ordinary and block kriging were chosen for this application. These also happen to be the default settings for the program. Default settings in the Geo-EAS program were used in most cases for sake of simplicity and speed, but mainly because they were the best choices for this application, as evidenced above.

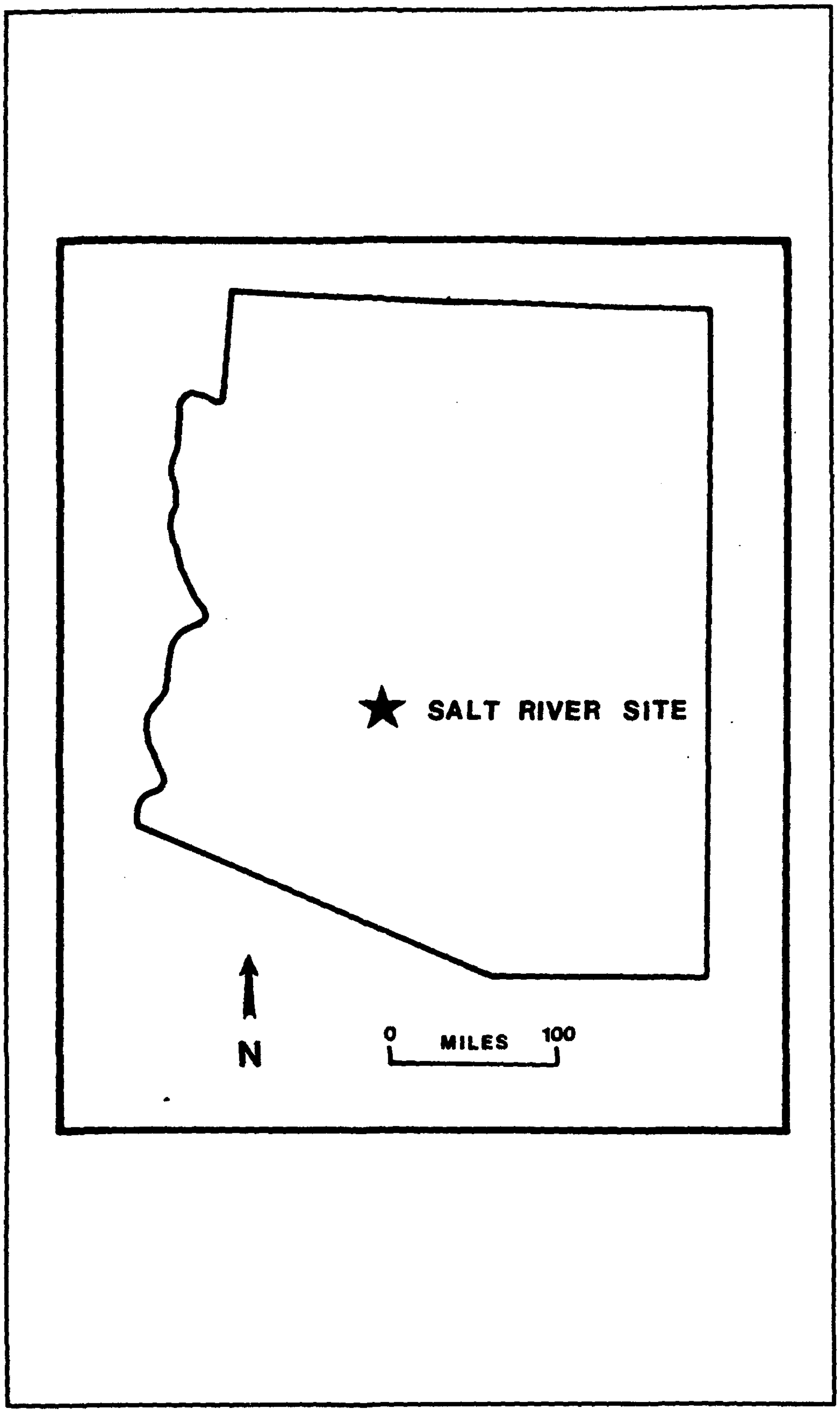

Figure 61. General location of the Salt River site

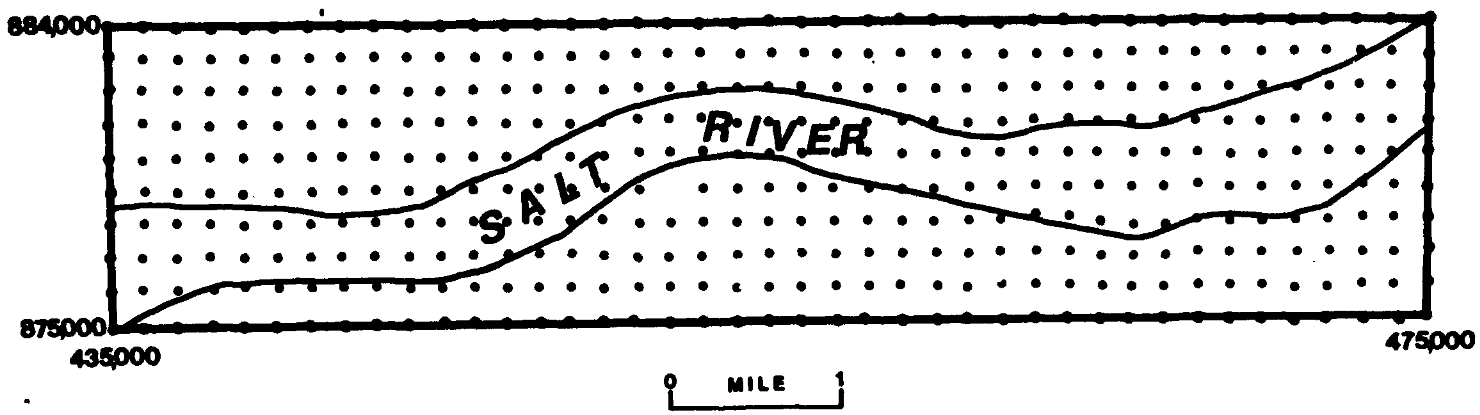

Figure 62. Floodplain boundaries and data point locations for the Salt River

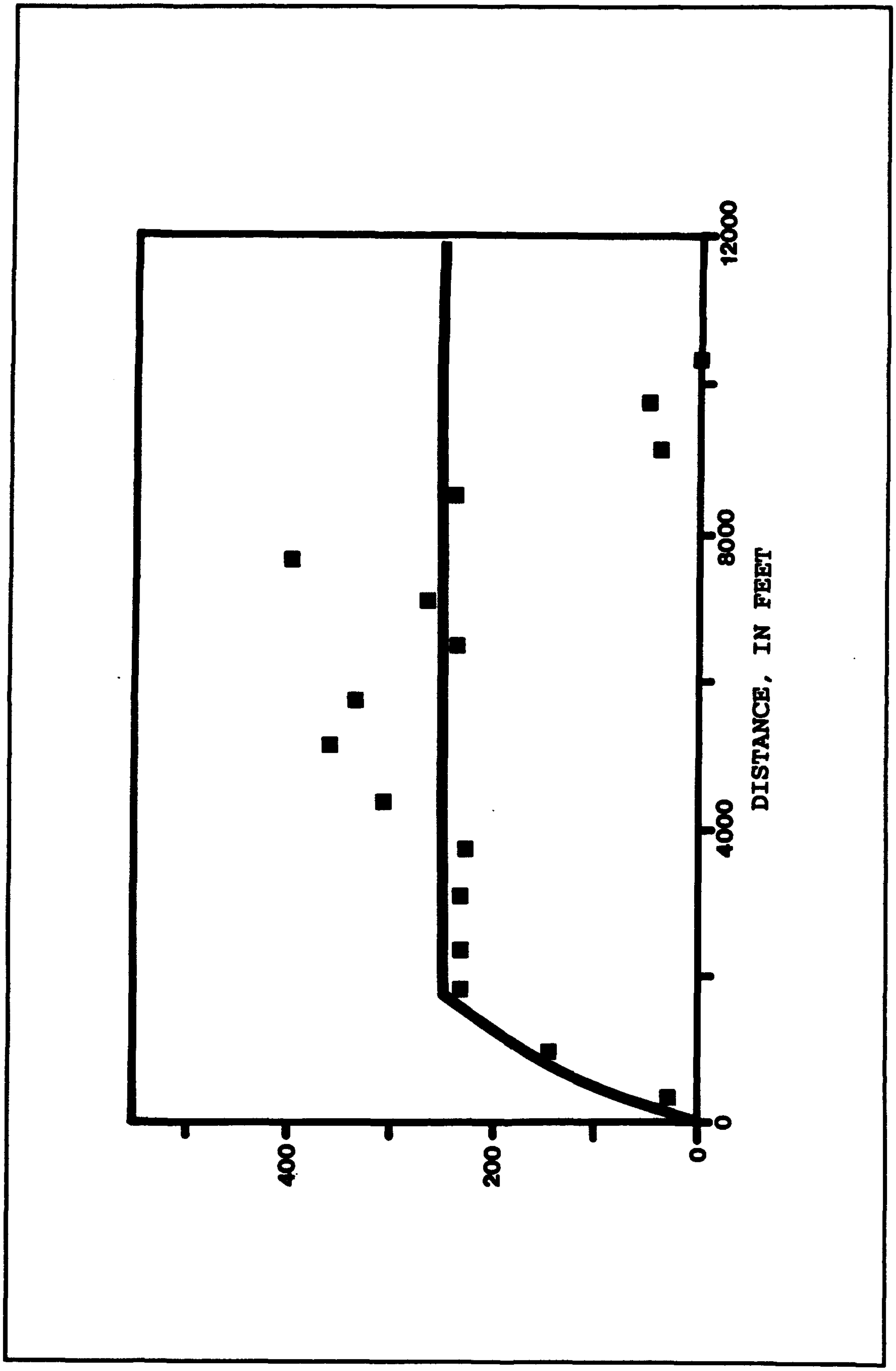

Figure 63. Variogram for all the data at the Rocky Mountain Arsenal (each plot may represent more than one data point)

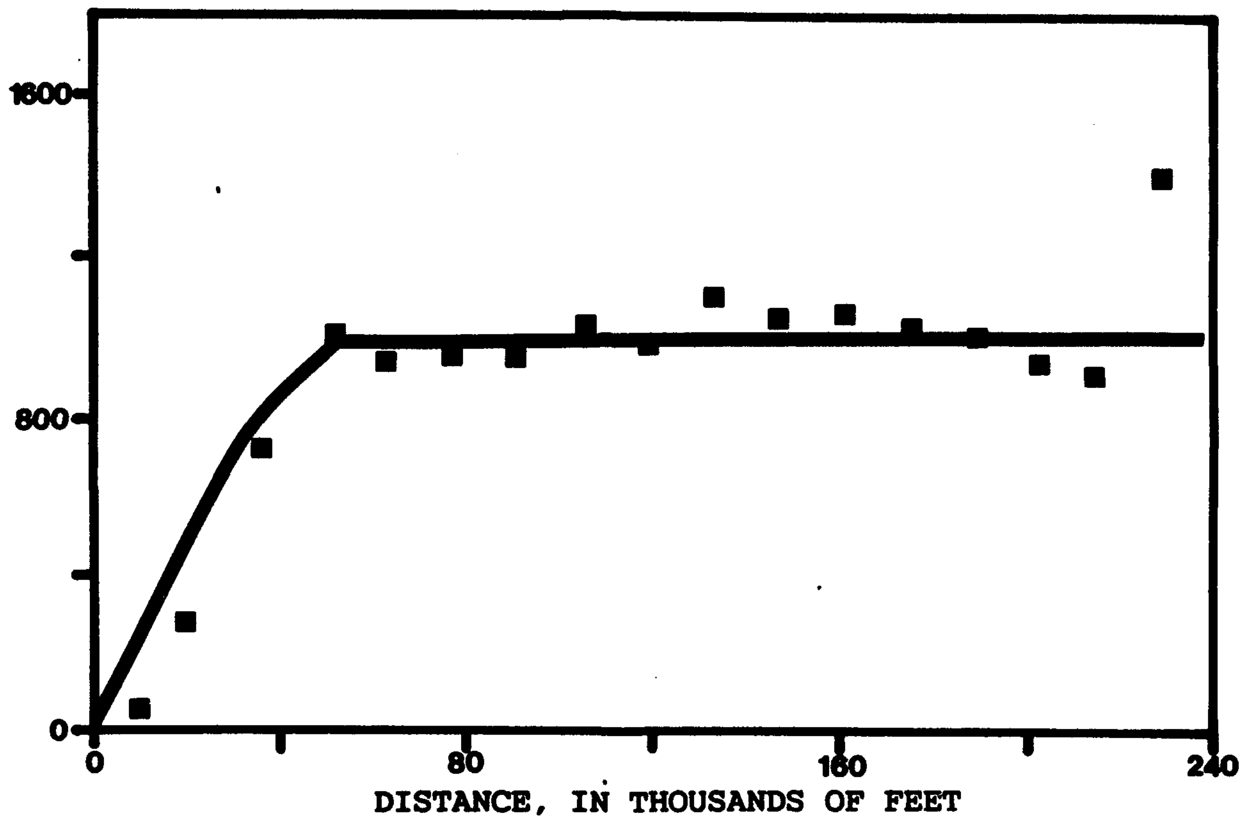

Figure 64. Variogram for the Brazos River data (each plot may represent more than one data point)

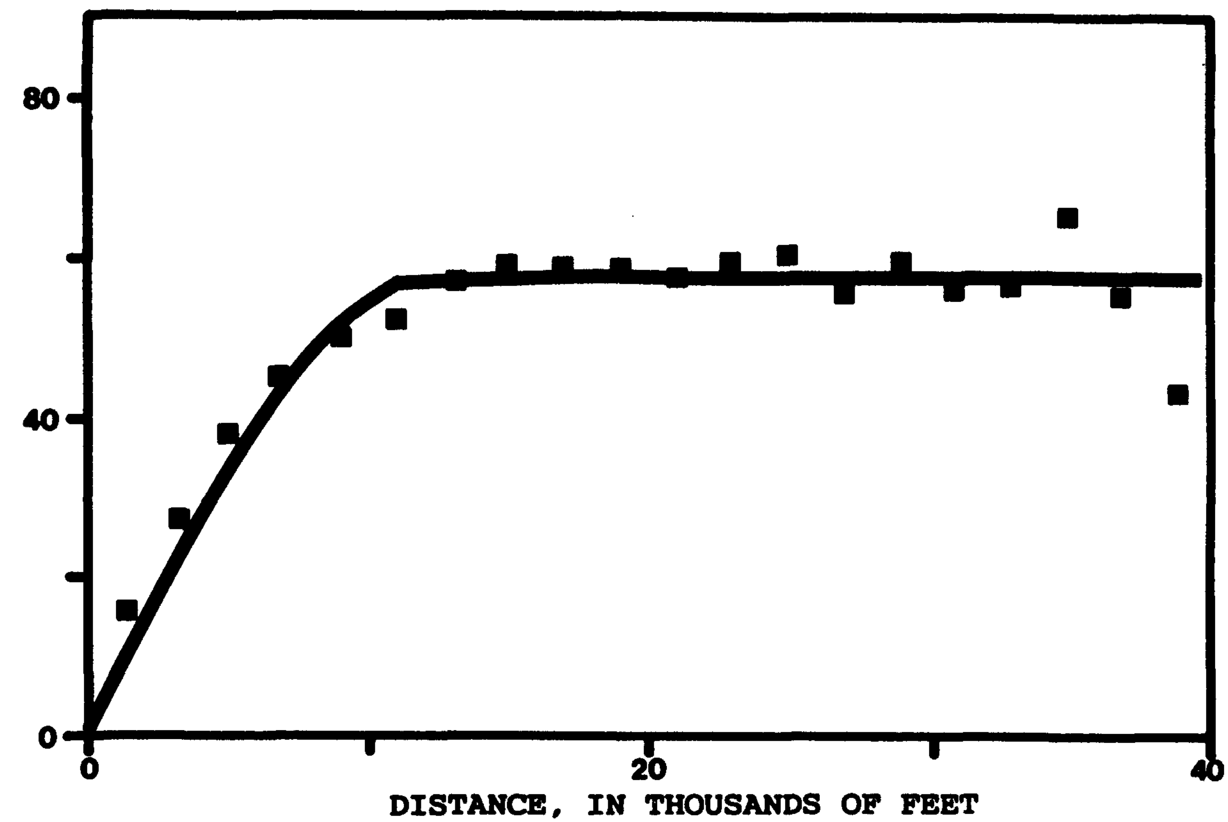

Figure 65. Variogram for the Salt River data (each plot may represent more than one data point)

The kriging portion of the Geo-EAS program produces estimates of the variable and the standard deviation of those estimates in a grid spacing which is contoured. Thickness was the variable for this application. The thickness was contoured in order to compare the results of the computer program to that produced by other methods, as at Rocky Mountain Arsenal, or that which was known, as that for the Brazos and Salt Rivers. The Brazos and Salt River sites' actual boundaries are shown in Figures 40 and 62. The boundaries shown by the thickness estimates can be seen in Figures 54 and 66. The comparison for the sites with known widths shows good reproduction of the sand bodies by the estimated thicknesses. The standard deviations of the thickness estimates were used in part to chose locations for additional information and in part to establish confidence of the estimated thickness. These have already been discussed previously in the Case Study and Supplemental Case Study sections.

The level of discussion presented in this section provides an overview of the geostatistics used in this application. A tutorial is provided in Appendix A for a more in depth understanding. Procedures can also be found in more depth from several source texts on the subject, such as in Davis (1986), and by Davis's suggestion, Clark (1979). Discussion of the techniques used and the operation of the Geo-EAS program is contained in Englund and Sparks (1988).

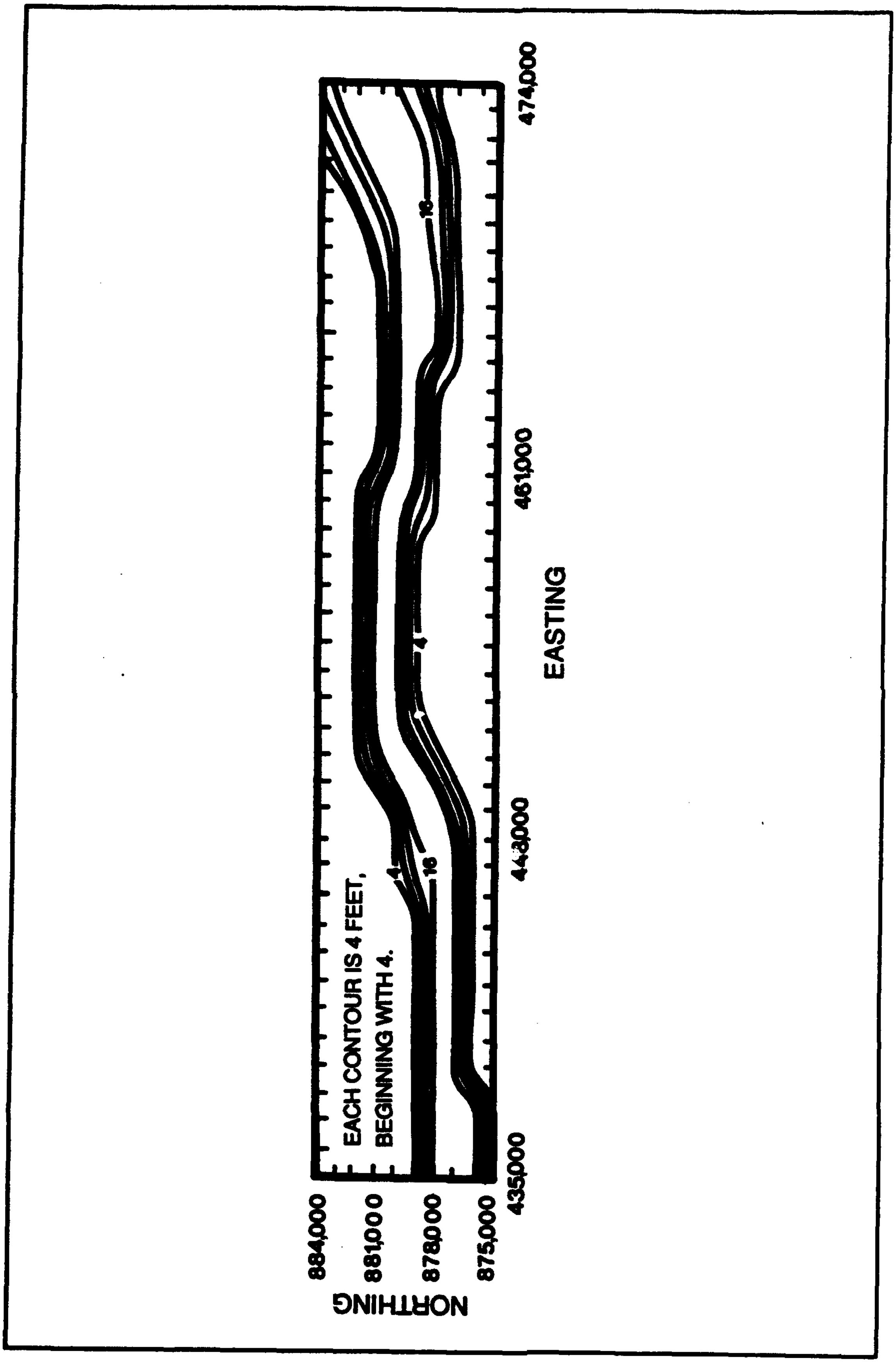

Figure 66. Estimated sand thickness from the Salt River 1000 foot grid

7 Predictive Model

As a result of the effort described in the preceding sections, a model was produced which predicts the location of data points needed in defining a discontinuous sand body. After having survived trials, as described in the Case Study, Supplemental Case Study and Geostatistics sections, the rationale for exploration has become the predictive model. The model is shown in Figure 67 and is described as follows.

The Model

The model as shown in Figure 67 begins initially, as any site investigation should, with a literature survey. The question is then asked, "Did the literature survey provide any information on which to base an exploration program?". If not, a minimum of three stratigraphic borings must be drilled to obtain the minimum information needed, the direction of dip of the bedrock of interest.

With the information, either from the literature survey or from boring information, priorities on which site boundaries should be drilled first are established. The priorities are based on the most likely orientation of any possible sand body.

Once the boundary priorities are established, a decision must be made as to whether surface geophysics can be used to explore for any sand body along the boundaries. If surface geophysics is a possibility, the method most applicable must be selected. If surface geophysics cannot be used, a drilling program must be initiated. The spacing for placement of the borings will depend on the application of the model.

During the exploration program and/or upon completion of it, the question, "Was a sand body encountered?" must be asked. If no sand was encountered, the question then posed is whether the exploration program is complete or not. If the exploration program is complete, then the model is ended with no sand body having been found. If the exploration program is not complete, the model is reentered by continued exploration inward from the boundary. This cycle or loop would continue until no sand was found and the exploration program was completed, or until a sand body was encountered.

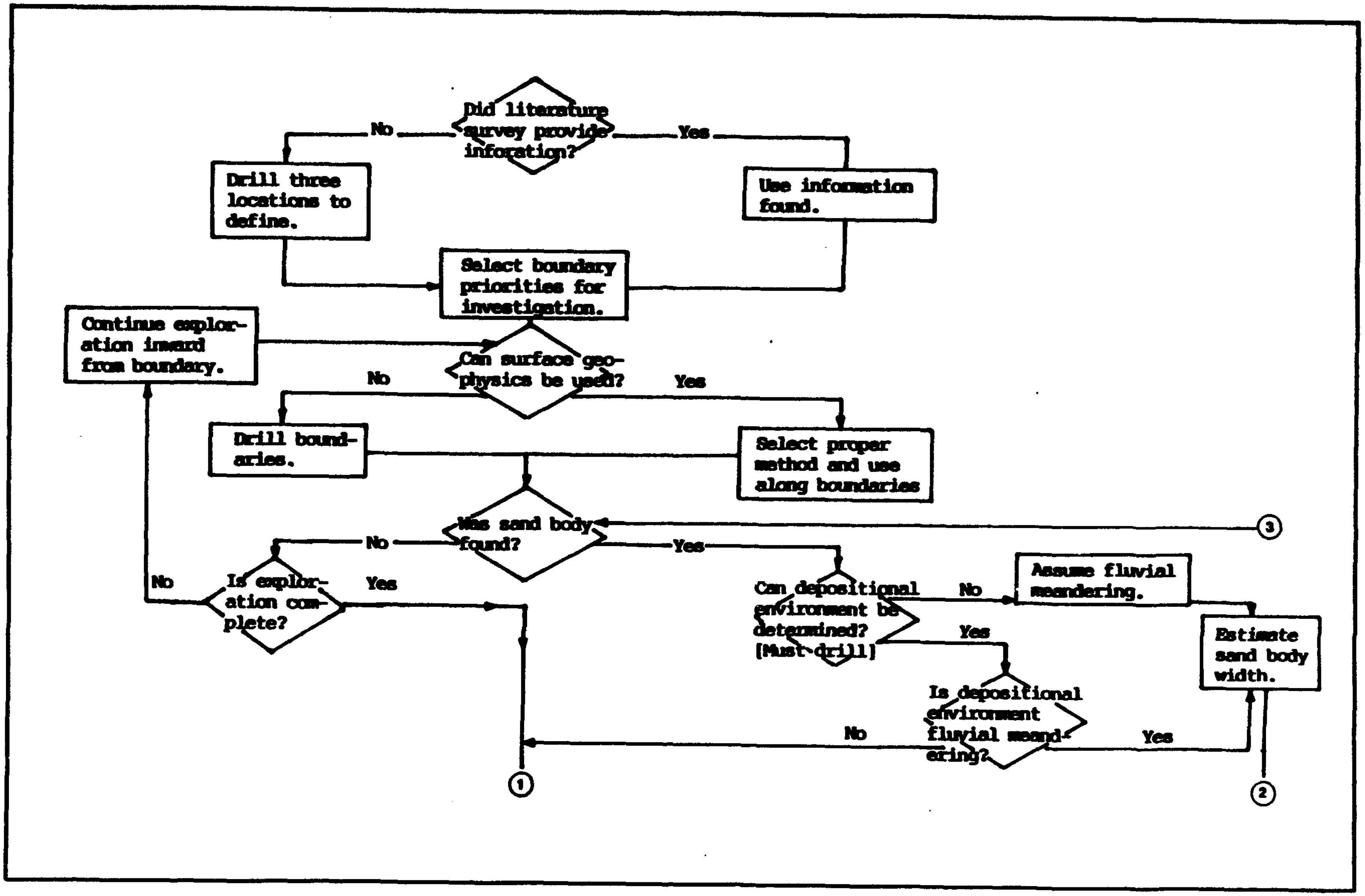

Figure 67. Predictive model (Continued)

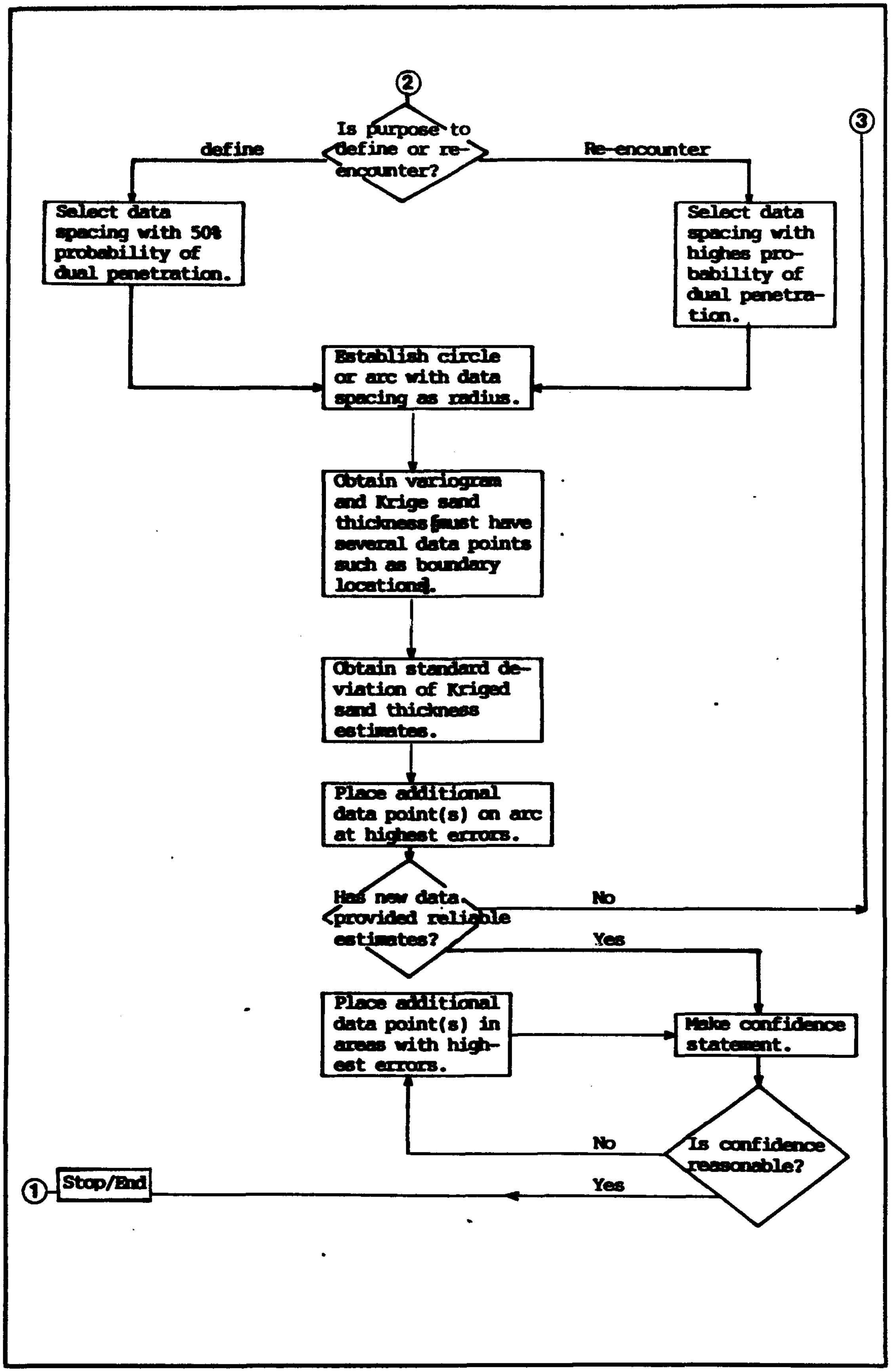

Figure 67. (Concluded)

At any time, if a sand body is encountered, the question, "Can the environment of deposition be determined?" must be asked. This requires that a possible sand body found by surface geophysical methods be drilled, to obtain the information necessary to make the environment of deposition determination. If the environment of deposition can be determined, it must be determined to be that of a meandering stream. If it is not, the model ends, since a requirement for this model is that the sand body is deposited by a meandering stream. If the environment of deposition is fluvial and meandering, or if it is assumed to be fluvial and meandering (the environment of deposition not determinable), the sand body width is estimated.

The next step in the model, following estimation of the sand body width, is dependent upon the purpose for which the model is being used. If the model is being used to define a sand body, as would be typical for an environmental application, a data or well spacing that has a 50 percent probability of dual penetration of the sand body is chosen. If the model is being used to reencounter the sand body, as would be typical for an oil and gas application, a data or well spacing that has the highest possible probability of dual penetration is selected within the spacing restrictions for which the model is being used. In either case, the data or well spacing is picked from the curves in Figure 5.

Using the data or well spacing distance as the radius from well(s) penetrating the sand body, circle(s) or arc(s) are drawn.

Using the Geo-EAS program, the standard deviations for estimated sand thicknesses produced by kriging is contoured from the current data set.

Additional data point(s) or well(s) are placed in location(s) on the circle or arc where the standard deviation shows that the thickness estimates standard deviation is greater than that of the standard deviation for the whole set of data, or, where the thickness estimates standard deviation is the highest. If more than one data location is placed along the circle or arc, they are separated by the data or well spacing obtained for the radius of the circle or arc.

The next step in the model is answering the question, "Has the data set, to date, created a reasonable estimate of thickness for the area of interest (i.e. the sand body)?". If not, the model must be reentered with the question "Was a sand body encountered?" (with the most recent addition to the data set). It should be noted that when reentered at this point, each subsequent portion of the model is redone. This includes calculating new sand body widths estimates, selecting new data or well spacings, etc. If and/or when the area of interest does show sand thickness standard deviations less than the standard deviation of the whole data set, then a confidence statement is made.

The confidence statement is the thickness estimate + or - the standard deviation for the kriged area. If the standard deviation is greater than the thickness, then it cannot be said that the sand is present. In this case, additional data or boring locations must be added, in locations of the highest standard deviations and then reenter the model by making a new confidence

statement. Once the confidence statement is reasonable, (i.e. the standard deviation is less than the estimated thickness) the model is completed.

If a sand body is encountered, meeting the conditions required to take the model to completion will normally require cycling through the model several times, reentering through the "Was a sand body encountered?" section. Through this process, the exploration program will follow the sand body through the site.

8 Conclusion

The research described in this report was directed at developing a method to minimize the data needed to define a discontinuous sand body. Since most populated areas are located adjacent to streams, the fluvially deposited sand body was the specific type targeted by this research. The purpose of the research was to minimize the hazards and costs associated with the exploration of such sand bodies, particularly at contaminated sites. Minimizing the number of borings necessary to define a fluvial sand body was accomplished by bringing geology into the exploration by predicting the location for needed data, based on determining the geometry of a sand body, once it was encountered, and by using any data already available.

The geometry of the sand body was determined by establishing the environment of deposition from stratigraphic data such as lithology, geophysical logs, grain size analysis, and the amount of quartz present. Once the environment of deposition was determined to be fluvial and meandering, the thickness of the sand was used to estimate a width for the sand body, using Leeder's (1973) and Lorenz and others' (1985) equations. This procedure required several assumptions and contained errors (based on geological variations), but produced a satisfactory estimate of the sand body width. From the sand body width, a data point spacing was obtained from the probability of penetrating the sand a second time.

By using the data from locations already in existence, such as that created by boundary drilling exploration, the thickness was kriged using the Geo-EAS program. This produced a grid of estimates of the sand body thicknesses, and perhaps more importantly, the error of those estimates (as the standard deviation). By comparing the standard deviation of the estimates with the standard deviation for the entire data set, new data point locations could be chosen in areas where the sand thickness standard deviations were greater than the standard deviation of the whole data set, or in areas with the most error, at the data point spacing needed.

The procedure described above was followed until the sand body was defined. By using this method, the sand body was defined with significantly fewer data point locations than required by typical grid methods of exploration.

This rationale for exploration was applied to the Rocky Mountain Arsenal, where the sand body was defined to the point where the standard deviation of the sand thicknesses were less than that of the whole data set. The exploration already conducted at the Arsenal had not defined the sand body to a point where the standard deviation of the sand thicknesses were less than that of the whole data set, thus, a planned comparison for accuracy could not be made. This resulted in a supplemental site being used for comparison purposes.

Since the Arsenal site supported the stratigraphic determination portion of the rationale for exploration, the supplemental site was chosen as a modern floodplain whose width could be visually established. Using this known width, a thickness was obtained and used as the thickness of the sand body at all locations. The site chosen was that of the Brazos River. Hypothetical exploration programs were then conducted to define the sand body, using the rationale for exploration and a typical grid exploration method. The results of each method of exploration were then compared. The comparison showed that the rationale for exploration had defined the hypothetical sand body with significantly fewer data points, but with similar accuracy of that of the grid method.

Variograms used to krige during the hypothetical explorations at the Arsenal site and for the Brazos River site had to be justified, because, normally large data sets are required to produce the variogram. All the data defining the sand body at the Arsenal, and close spaced grid data from the Brazos River and the Salt River were used to create variograms. These variograms from the large data sets indicated that variograms used in the limited data explorations were justified.

Having survived the test case applications, the rationale for exploration became the predictive model for defining a fluvial sand body.

Thus, based on the research described, the predictive model which was developed can be used to select data point locations in defining a fluvial sand body by following the sand body into and through the site. This is accomplished by bringing geologically based statistical methods into the exploration program. By doing this, significantly fewer data points are needed to define the sand body than needed by the typical grid method, which is commonly used. The lower number of data points reduces the hazard and cost associated with the exploration program.

9 Recommendations

Based on the findings of this research the following recommendations are made:

a. The conclusion that the predictive model defined a discontinuous sand body with a minimum number of data point locations is based on limited testing. Additional sites should be tested. These need to be of various size fluvial sand bodies, from different locations, in different climates, of different ages, for varying amounts of initial data, and for different applications.

b. Although the findings of this research shows that the predictive model reduces the number of data point locations needed to define a discontinuous sand body, existing or visible data was used. The model should be used during actual exploration programs for determining "in the field" applicability.

c. The confidence statements which were made for the defined sand bodies in this research shows large errors, particularly at the smaller thicknesses. These confidence statements were made based on the assumption that the distribution of the data is normal, even though a normal distribution can give a physically impossible sand body thickness (negative about a zero or small thickness). This is because the functions which may better describe the variable's distribution, such as log-normal or beta, need a relatively large amount of data to even establish which function would be best. More data than this application usually will usually provide. Additionally, little work has been published to advance the state of the art for these functions. Further investigation needs to address the use of non-normal distribution functions.

d. Investigations should be conducted to determine if the predictive model developed in this research can be adapted to stacked fluvial meander belt sand bodies, in a layered sequence.

e. Other environments of deposition for discontinuous sand bodies need to be researched in order to determine if predictive models can be developed to reduce the number of data point locations needed to define them.

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Appendix A
Kriging Tutorial

Overview

Geostatistical methods are useful for site assessment where data are collected on a spacial network of sampling locations. Kriging is a weighted moving average method used to interpolate values from a sample data set onto a grid of points for contouring. The kriging weights are computed from a variogram, which measures the degree of correlation among sample values in the area as a function of the distance and direction between samples (Englund and Sparks 1988). This tutorial will provide a glossary of geostatistical terms adapted from Englund and Sparks, 1988; a discussion of kriging, with the kriging equation; a discussion of variograms, with explanations of the different models; and a simple example showing calculations.

Glossary

Block Kriging - Estimating the value of a block, centered on a specific grid node, from a set of nearby sample values using kriging.

Covariance - A statistical measure of the correlation between two variables. Covariance is usually treated as the simple inverse of the variogram, computed as the overall sample variance minus the variogram value.

Exponential Model - A function frequently used when fitting mathematical models to experimental variograms.

Gaussian Model - A function frequently used when fitting mathematical models to experimental variograms.

Kriging Standard Deviation - The standard error of estimation computed for a kriged estimate. Kriging is the weighted linear estimate with the particular set of weights which minimizes the computed estimation variance (standard error squared). The relationship of the kriging standard deviation to the actual

error of estimation is very dependent on the variogram model used and the validity of the underlying assumptions.

Linear Model - A function frequently used when fitting mathematical models to experimental variograms.

Madogram - A plot of mean absolute difference of paired sample measurements as a function of distance and direction. Madograms are not true variograms, and generally should not be used in kriging. The kriging standard deviations will be meaningless.

Nugget Model - A constant variance model most often used in combination with one or more other functions when fitting mathematical models to experimental variograms.

Ordinary Kriging - A variety of kriging which assumes that local means are not necessarily closed related to the population mean, and which therefore uses only the samples in the local neighborhood for the estimate. Ordinary kriging is the most commonly used method for environmental situations.

Point Kriging - Estimating the value of a point from a set of nearby sample values using kriging. The kriged estimate for a point will usually be quite similar to the kriged estimate for a relatively small block centered on the point, but the computed kriging standard deviation will be higher. When a kriged point happens to coincide with a sampled location, the kriged estimate will equal the sample value.

Range - The distance at which a variogram model reaches its maximum value, or sill.

Semi-Variogram - There is disagreement in the geostatistical literature as to whether "semi-variogram" or "variogram" should be used, but they have the same meaning.

Sill - The upper limit of any variogram model.

Simple Kriging - A variety of kriging which assumes that local means are relatively constant and equal to the population mean, which is known. The population mean is used as a factor in each local estimate, along with the samples in the local neighborhood.

Spherical Model - A function frequently used when fitting mathematical models to experimental variograms.

Variogram - A plot of the variance (one-half the mean squared difference) of paired sample measurements as a function of the distance (and optionally of the direction) between samples. Typically, all possible sample pairs are examined and grouped into classes (called lags) of approximately equal distance and direction. Variograms provide a means of quantifying the

commonly observed relationship that samples close together will tend to have more similar values than samples far apart.

Variograms

Englund and Sparks (1988) state that the computation, interpretation, and modeling of variograms is the "heart" of a geostatistical study. The variogram model is the interpretation of the spatial correlation structure of the sample data set. It controls the way that kriging weights are assigned to samples during interpolation, and consequently controls the quality of the results.

All interpolation and contouring methods make the assumption that some type of spatial correlation is present. They assume that a measurement at any point represents nearby locations better than locations farther away. Variogram analysis attempts to quantify the relationship of how well a measurement can be expected to represent another location a specific distance away. Variograms plot the average difference (actually, one-half the squared difference, or variance) of pairs of measurements against the distances separating the pairs. If measurements were possible at all sample locations, a "true" variogram could be computed for a site showing the variance of all pairs of measurements which satisfy each combination of distance and direction. In practice, with limited data, variances are computed for groups of pairs of measurements in class intervals of similar distance and direction. Then a graph is plotted of the variances versus distance. Then a model curve is fitted to the graph. The model is assumed to be an approximation of the "true" variogram.

Davis (1986) describes the semivariogram in a similar manor, exemplifying the use of a different term for the variogram. Davis (1986) continues his presentation of the "semivariogram" by assuming that the samples are point measurements of a property. For computational tractability, the assumption is also made that the samples are uniformly spaced along straight lines. If the spacing between samples along a line is some distance Δ, the semivariance, γ_h, can be estimated for distances that are multiples of Δ:

$$\gamma_h = \sum_i^{n-h} (X_i - X_{i+h})^2/2n$$

In this notation, X_i, is a measurement of a regionalized variable taken at location i, and X_{i+h} is another measurement taken h intervals away. We are therefore finding the sum of the squared differences between pairs of points separated by the distance Δh. The number of points is n, so the number of comparisons between pairs of points is n - h.

If the semivariances are calculated for different values of h, the results can be plotted in the form of a semivariogram (i.e. variogram). When the distance between sample points is zero, the value at each point is being compared with itself. Hence, all the differences are zero, and the semivariance for γ_0 is zero. If Δh is a small distance, the points being compared tend to be very

similar, and the semivariance will be a small value. As the distance Δh is increased, the points being compared are less and less closely related to each other and their differences become larger resulting in larger values of γ_h. At some distance the points being compared are so far apart that they are not related to each other, and their squared differences become equal in magnitude to the variance around the average value. The semivariance no longer increases and the semivariogram develops a flat region called a sill. The distance at which the semivariance approaches the variance is referred to as the range (or span) of the regionalized variable, and defines a neighborhood within which all locations are related to one another.

For some arbitrary point in space, the neighborhood can be envisioned as a symmetrical interval about the point. If the regionalized variable is stationary, or has the same average value everywhere, any locations outside the interval are completely independent of the central point, and cannot provide information about the value of the regionalized variable at that location. Within the neighborhood, however, the regionalized variable at all observation points is related to the regionalized variable at the central location and hence can be used to estimate its value. If a number of measurements are used, made at locations within the neighborhood to estimate the value of the regionalized variable at the central location, the semivariogram provides the proper weightings to be assigned to each of these measurements.

The semivariogram expresses the spatial behavior of the regionalized variable or its residual. A reasonable form for the semivariogram must be assumed and used as a first approximation. A semivariogram tangent to the X axis at the origin is described as parabolic and indicates that the regionalized variable is exceptionally continuous. A variogram that is linear in form indicates moderate continuity of the regionalized variable. A truly random variable will have no continuity and its semivariogram will ba a horizontal line equal to the variance. In some circumstances the semivariogram will appear to not go through the origin but rather will assume some nonzero value. This is referred to as the "nugget effect". In theory, γ_0 must equal zero. The nugget effect arises because the regionalized variable is so erratic over a very short distance that the semivariogram goes from zero to the level of the nugget effect in a distance less than the sampling interval.

In principle, the experimental semivariogram could be used directly to provide values for estimation procedures. However, the semivariogram is known only at discrete points representing distances Δh. In practice, semivariances may be required for any distance, whether a multiple of Δ or not. For this reason, the discrete experimental semivariogram must be modelled by a continuous function that can be evaluated for any desired distance. Fitting a model equation to an experimental semivariogram is a trial-and-error process, usually done by eye. Ideally, the model chosen to represent the semivariogram should begin at the origin, rise smoothly to some upper limit, then continue at a constant level.

The spherical model has these properties. For a distance, h, less than the range, R, it is defined as:

$$\gamma_h = \gamma_s \frac{3h}{2R} - \frac{h^3}{2R^3}$$

for all distances up to the range, R, of the semivariogram. Beyond the range, the semivariance, γ_h, equals the variance, γ_s. The spherical model, shown in the following diagram, usually is described as the ideal form of the semivariogram. Another that is sometimes used is the exponential model:

$$\gamma_h = \gamma_s \, (1-e^{-h/R})$$

The exponential model, shown in the following diagram, never quite reaches the limiting value of the sill, but approaches it asymptotically. Also, the semivariance of the exponential model is lower than the spherical for all values of h less than the range.

The linear model, is simpler than either the spherical or exponential, because it has only one parameter, the slope α. The model has the form:

$$\gamma_h = \alpha h$$

and plots as a straight line through the origin. This model cannot have a sill, as it rises without limit. Sometimes, as shown in the following diagram, the linear model is arbitrarily modified by inserting a sharp break at the sill value. The use of such a model has been criticized because the kriging estimation procedure presumes the semivariogram is a continuous smoothly varying function. If the regionalized variable has been sampled at a sufficient density, relative to the range, there will be no significant differences between estimates made assuming a linear model and those obtained using a spherical or other model.

Kriging

According to Davis (1986) kriging addresses a regionalized variable, which is a naturally occurring property that has characteristics intermediate between a truly random variable and one that is completely deterministic. Many geological surfaces, both real and conceptual, can be regarded as regionalized variables. These are continuous from place to place and therefore must be spatially correlated over short distances. However, points on an irregular surface that are widely separated tend to be statistically independent. The degree of spatial continuity of a regionalized variable can be expressed by a semivariogram. If measurements have been made at scattered sampling points

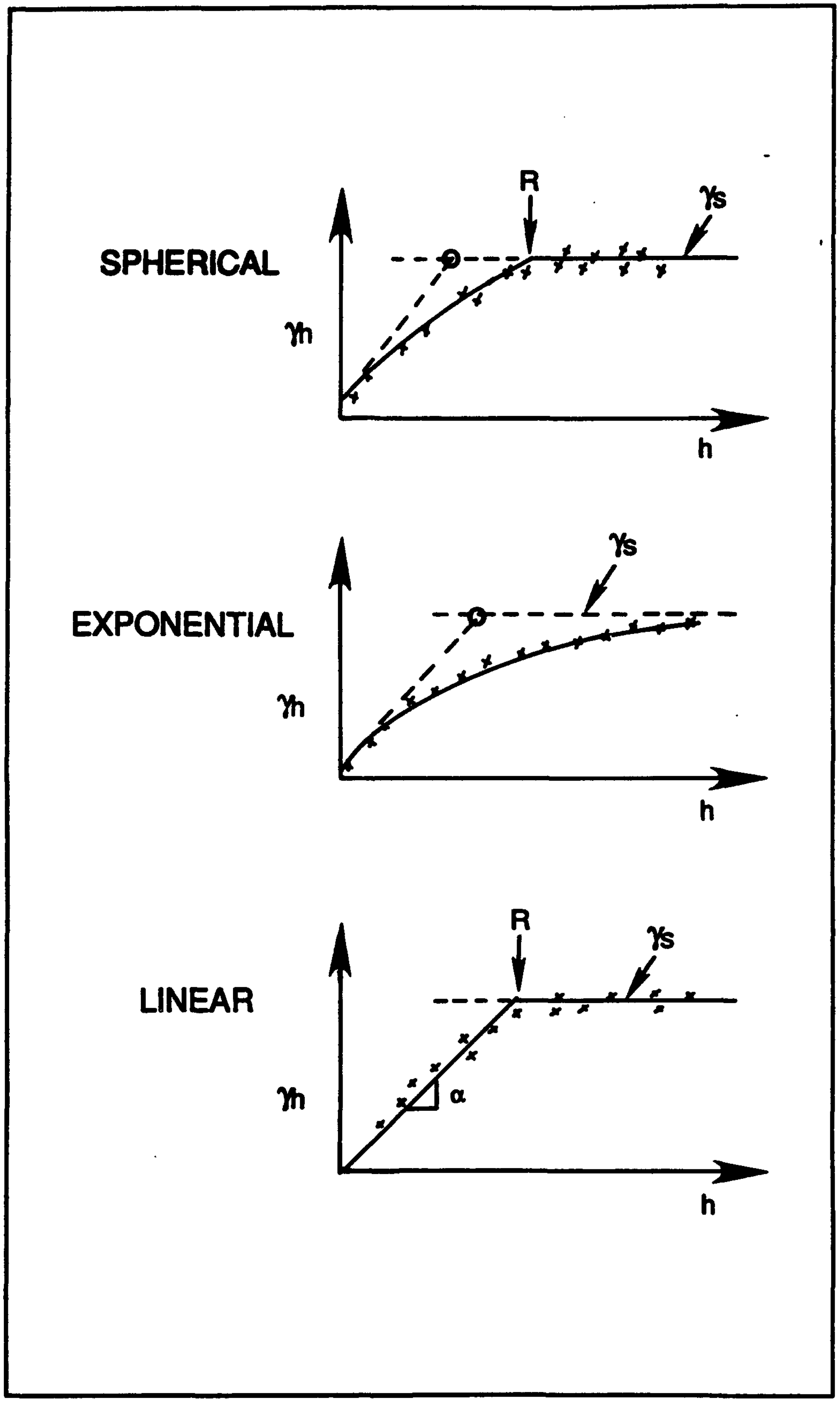


Figure 1. Variogram models

and the form of the semivariogram is known, it is possible to estimate the value of the surface at any unsampled location. This estimation procedure is called kriging, named after K.G. Krige, a South African mining engineer and pioneer in the application of statistical techniques to mine evaluation.

Kriging can be used to make contour maps, but unlike conventional contouring algorithms, it has certain statistically optimal properties. Perhaps most importantly, the method provides measures of the error or uncertainty of the contoured surface. Kriging uses the information from the semivariogram to find an optimal set of weights that are used in the estimation of the surface at unsampled locations. Since the semivariogram is a function of distance, the weights change according to the geographic arrangement of the samples.

Point, or Punctual according to Davis (1986), is the simplest form of kriging, in which the observations consist of measurements taken at dimensionless points, and the estimates are made at other locations that are dimensionless points. Punctual kriging is used in contour mapping where the observations may be from a set of exploratory drill holes. Constructing a map requires that estimations of the variable be made at closely spaced locations over the map area. Once made, contour lines can be drawn through these estimates.

To simplify the operation, it can be assumed that the variable being mapped is statistically stationary, or free from drift. The value at an unsampled location may be estimated as a weighted average of the known observations, of weight W. The value, Y, at a point, p, is based on a small set of nearby known points:

$$Y'_p = \sum W_i Y_i$$

It is expected that the estimated value, Y'_p, will differ somewhat from the true (but unknown) value, Y_p, by an amount that is called the estimation error, ϵ_p:

$$\epsilon_p = (Y'_p - Y_p)$$

If the weights used in the estimation equation sum to one, the resulting estimates are unbiased. This means that, over a great many estimations, the average error will be zero, as overestimates and underestimates will tend to cancel one another. However, the estimates may scatter widely about the correct values. This scatter can be expressed as the error variance, S^2_ϵ,

$$S^2_\epsilon = \frac{\sum (Y'_p - Y_p)}{n}$$

or as its square root, the standard error of the estimate, S_ϵ:

$$S_\epsilon = \sqrt{S_\epsilon^2}$$

As noted, it seems intuitively reasonable that nearby known points should be most influential in estimating the value at an unsampled location, and that more distant control points should be less influential. It also seems reasonable to expect that the weights used in the estimation process, and the error in the estimate, should be related in some way to the semivariogram.

For example, to estimated the value of Y at a point p from three nearby points, using as our estimator a weighted average of the three known values:

$$Y'_p = W_1 Y_1 + W_2 Y_2 + W_3 Y_3$$

The weights are constrained to sum to one, so the estimate is unbiased if there is no trend. Suppose that weight W_1 is chosen to ge equal to 1.0. Then, weights W_2 and W_3 must be zero and the estimate at p is:

$$Y'_p = 1.0Y_1 + 0.0Y_2 + 0.0Y_3$$

or

$$Y'_p = Y_1$$

The estimation error is simply $\in = Y_p - Y_1$, since Y_1 is the estimate Y'_p. If many other locations like Y_p are estimated from points arranged in a manner spatially similar to Y_1, the estimation variance can be calculated as the average squared difference between these pairs of points. For convenience, these other estimated locations may be called Y_{pi} and the other estimating points Y_{1i}. Then,:

$$S_\epsilon^2 = 1/n \sum_{i=1}^{n} (Y_{pi} - Y_{1i})^2$$

The estimation variance is equal to twice the semivariance for a distance equal to the separation between points Y_{pi} and Y_{1i}.

A particular combination of weights have been chosen to arrive at an estimate Y'_p and to determine the estimation error. There are an infinite number of other possible combinations of weights that could be chosen, each of which will give a different estimate and a different estimation error. There is, however, only one combination that will give a minimum estimation error. It is this unique combination of weights that kriging attempts to find.

Deriving the kriging equations requires calculus and will not be considered here. A simple discussion is contained in Clark (1979) and a complete

derivation is provided by Olea (1975). Optimum values for the weights can be found by solving a set of simultaneous equations, which includes values from a semivariogram of the variable being estimated. The weights are optimal in the sense that the resulting estimates are unbiased and have minimum estimation variance. No other linear combination of the observations can yield estimates that have a smaller scatter around their true values.

To make a kriged estimate of the value Y' at a point p from three known observations, Y_1, Y_2, and Y_3, three weights, W_1, W_2, and W_3 must be found for the kriging equation. To find these requires the solution to a system of three simultaneous equations:

$$\begin{aligned}
W_1\,\gamma(h_{11}) + W_2\,\gamma(h_{12}) + W_3\,\gamma(h_{13}) &= \gamma(h_{1p})\\
W_1\,\gamma(h_{12}) + W_2\,\gamma(h_{22}) + W_3\,\gamma(h_{23}) &= \gamma(h_{2p})\\
W_1\,\gamma(h_{13}) + W_2\,\gamma(h_{23}) + W_3\,\gamma(h_{33}) &= \gamma(h_{3p})
\end{aligned}$$

In this notation, $\gamma(h_{ij})$ is the semivariance over a distance h corresponding to the separation between points i and j. For example, $\gamma(h_{13})$ is the semivariance for a distance equal to that between known points 1 and 3; $\gamma(h_{1p})$ is the semivariance for a distance equal to that between known point 1 and the location p, where the estimate is to be made. The left-hand matrix is symmetrical because $h_{ij} = h_{ji}$. It has zeroes along the main diagonal because h_{ij} represents the distance from a point to itself, which is zero. Assuming the semivariogram goes through the origin, the semivariance for zero distance is zero. Values of the semivariance are taken from the semivariogram, which must be known (or estimated) prior to kriging.

A fourth equation is needed to ensure that the solution is unbiased, by constraining the weights to sum to one:

$$W_1 + W_2 + W_3 = 1.0$$

This gives a set of four equations but only three unknowns. Since there are more equations than unknowns, an extra degree of freedom can be used to assure that the solution will have the minimum possible estimation error. This is done by adding a slack variable, called a Lagrange multiplier, λ, to the equation set. The complete set of simultaneous equations has the following appearance:

$$\begin{aligned}
W_1\,\gamma(h_{11}) + W_2\,\gamma(h_{12}) + W_3\,\gamma(h_{13}) + \lambda &= \gamma(h_{1p})\\
W_1\,\gamma(h_{12}) + W_2\,\gamma(h_{22}) + W_3\,\gamma(h_{23}) + \lambda &= \gamma(h_{2p})\\
W_1\,\gamma(h_{13}) + W_2\,\gamma(h_{23}) + W_3\,\gamma(h_{33}) + \lambda &= \gamma(h_{3p})\\
W_1 \quad + \quad W_2 \quad + \quad W_3 \quad + 0 &= 1
\end{aligned}$$

Rearranging in matrix form.

$$\begin{bmatrix} \gamma(h_{11}) & \gamma(h_{12}) & \gamma(h_{13}) & 1 \\ \gamma(h_{12}) & \gamma(h_{22}) & \gamma(h_{23}) & 1 \\ \gamma(h_{13}) & \gamma(h_{23}) & \gamma(h_{33}) & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \lambda \end{bmatrix} = \begin{bmatrix} \gamma(h_{1p}) \\ \gamma(h_{2p}) \\ \gamma(h_{3p}) \\ 1 \end{bmatrix}$$

In general terms the matrix equation must be solved:

$$[A] \cdot [W] = [B]$$

for the vector of unknown coefficients, [W]. The terms in matrix [A] and vector [B] are taken directly from the semivariogram or from the mathematical function that describes its form. Once the unknown weights have been determined, the variable at location p is estimated by:

$$Y'_p = W_1 Y_1 + W_2 Y_2 + W_3 Y_3$$

The estimation variance is:

$$S_\epsilon^2 = W_1\ \gamma(h_{1p}) + W_2\ \gamma(h_{2p}) + W_3\ \gamma(h_{3p}) + \lambda$$

The variance estimate is essentially the weighted sum of the semivariances for the distances to the points used in the estimation, plus a contribution from the λ coefficient that is equivalent to a constant term. Kriging has two powerful advantages over conventional estimation procedures such as those used for contour mapping. Kriging produces estimates that, on average, have the smallest possible error, and also produces an explicit statement of the magnitude of this error.

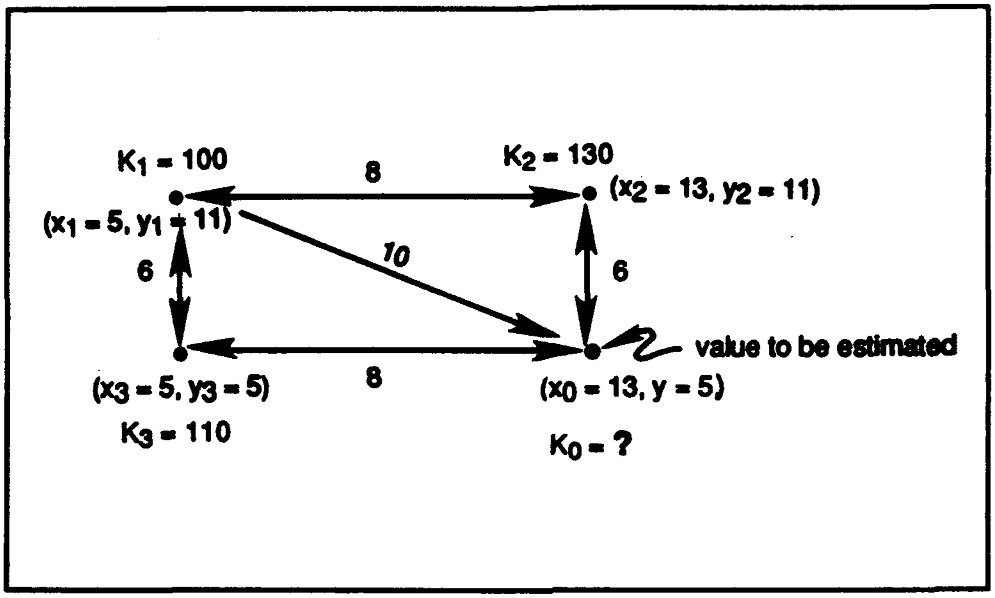
If the assumption is made that the errors of estimation are normally distributed about the true value, the standard error can be used as a confidence band around the estimates. The probability that the true value at point p is within one standard error above or below the value estimated is 68 percent, and the probability is 95 percent that the true elevation lies within two standard errors.

Although a normal distribution can give a physically impossible number in the case of variables which cannot have negative values, it is still used. A normal distribution is used because of a lack of documentation for other functions, such as log-normal and beta, even though they may give a more realistic distribution. Also, a significant amount of data is necessary to establish which function would give the most realistic distribution.

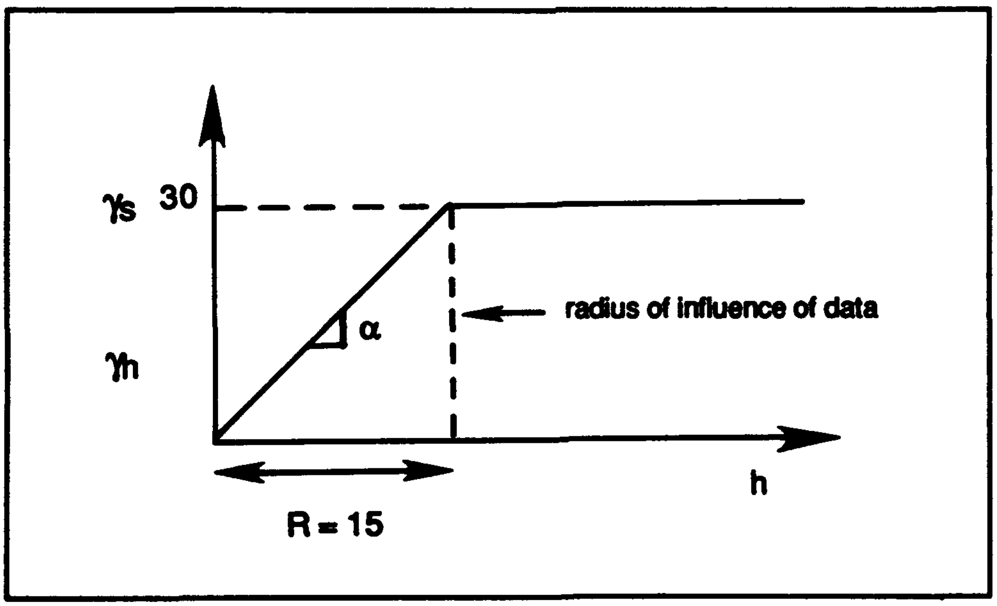
Example

The following is a simple example of Kriging:

Given a set of three observations K_1, K_2, and K_3, estimate K_o by kriging.



Assume a known semivariogram (i.e. variogram) model. In this case the relatively simple linear semivariogram is used.



$$\gamma h = \alpha h \text{ where } \alpha = 2 = slope$$
$$\gamma h = 2h \quad for\ h \leq R = 15$$

Using the matrix form of the kriging equation:

$$\begin{bmatrix} \gamma(h_{11}) & \gamma(h_{12}) & \gamma(h_{13}) & 1 \\ \gamma(h_{12}) & \gamma(h_{22}) & \gamma(h_{23}) & 1 \\ \gamma(h_{13}) & \gamma(h_{23}) & \gamma(h_{33}) & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \lambda \end{bmatrix} = \begin{bmatrix} \gamma(h_{1p}) \\ \gamma(h_{2p}) \\ \gamma(h_{3p}) \\ 1 \end{bmatrix}$$

then:

$$\begin{bmatrix} \gamma(x_1-x_1) & \gamma(x_2-x_1) & \gamma(x_3-x_1) & 1 \\ \gamma(x_1-x_2) & \gamma(x_2-x_2) & \gamma(x_3-x_2) & 1 \\ \gamma(x_1-x_3) & \gamma(x_2-x_3) & \gamma(x_3-x_3) & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \lambda \end{bmatrix} = \begin{bmatrix} \gamma(x_0-x_1) \\ \gamma(x_0-x_2) \\ \gamma(x_0-x_3) \\ 1 \end{bmatrix}$$

so:

$$\begin{bmatrix} \gamma(0) & \gamma(8) & \gamma(6) & 1 \\ \gamma(8) & \gamma(0) & \gamma(10) & 1 \\ \gamma(6) & \gamma(10) & \gamma(10) & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \lambda \end{bmatrix} = \begin{bmatrix} \gamma(10) \\ \gamma(6) \\ \gamma(8) \\ 1 \end{bmatrix}$$

where:

$$\gamma h = 2h$$

so:

$$\begin{aligned} \gamma(0) &= 0 \\ \gamma(6) &= 12 \\ \gamma(8) &= 16 \\ \gamma(10) &= 20 \end{aligned}$$

and:

$$\begin{bmatrix} 0 & 16 & 12 & 1 \\ 16 & 0 & 20 & 1 \\ 12 & 20 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \lambda \end{bmatrix} = \begin{bmatrix} 20 \\ 12 \\ 16 \\ 1 \end{bmatrix}$$

Invert the matrix to solve for W_1, W_2, W_3, and

where the W's are the kriging weights and λ is the Lagrange multiplier.

$$\begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \lambda \end{bmatrix} = \begin{bmatrix} -.05681 & .022727 & .34090 & .227272 \\ .022727 & -.03409 & .011363 & .409090 \\ .034090 & .011363 & .04545 & .363636 \\ .227272 & .409050 & .363636 & -10.9090 \end{bmatrix} \begin{bmatrix} 20 \\ 12 \\ 16 \\ 1 \end{bmatrix}$$

$$W_1 = -.09090$$
$$W_2 = .636363$$
$$W_3 = .454545$$
$$\lambda = 4.363636$$

Note that the W's sum to 1 for the unbiased requirement.

$$K_0 = W_1K_1 + W_2K_2 + W_3K_3$$

so:

$$K_0 = 123.64$$

To obtain the kriging variance:

$$S_\epsilon^2 = W_1\ \gamma(h_{1p}) + W_2\ \gamma(h_{2p}) + W_3\ \gamma(h_{3p}) + \lambda$$

or:

$$S_\epsilon^2 = W_1\ \gamma(x_1-x_0) + W_2\ \gamma(x_2-x_0) + W_3\ \gamma(x_3-x_0) + \lambda$$

which is:

$$= W_1\ \gamma(10) + W_2\ \gamma(6) + W_3\ \gamma(8) + \lambda$$

$$= -.09090(20) + .6363(12) + .4545(16) + 4.36$$

$$= 13.09$$

and:

$$S_\epsilon = 3.62$$

If K has a normal distribution then

$$K_{true} = K_0 \pm 2S_\epsilon \textit{ with 95 percent probability}$$

$$K_0 + 2S_\epsilon = 123.64 + 2(3.62) = 130.88$$

$$K_0 - 2S_\epsilon = 123.64 - 2(3.62) = 116.38$$

so:

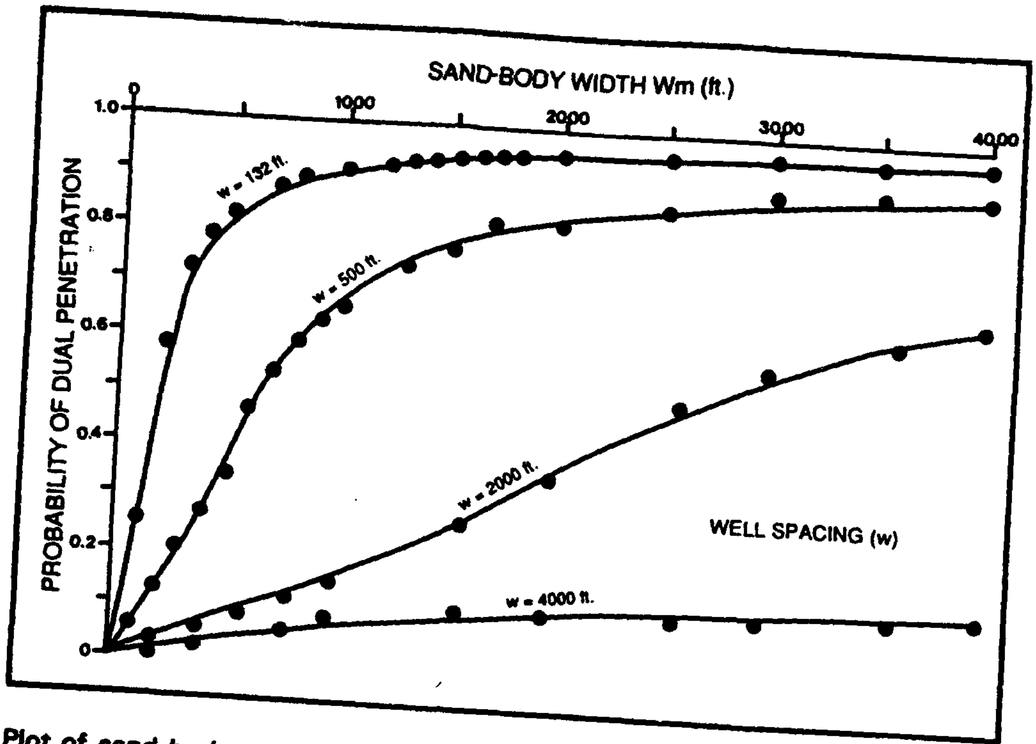
$$116.38 \leq K_{true} \leq 130.88 \textit{ with 95 percent confidence}$$

Appendix B
Data from Probability of Dual Penetration Calculations

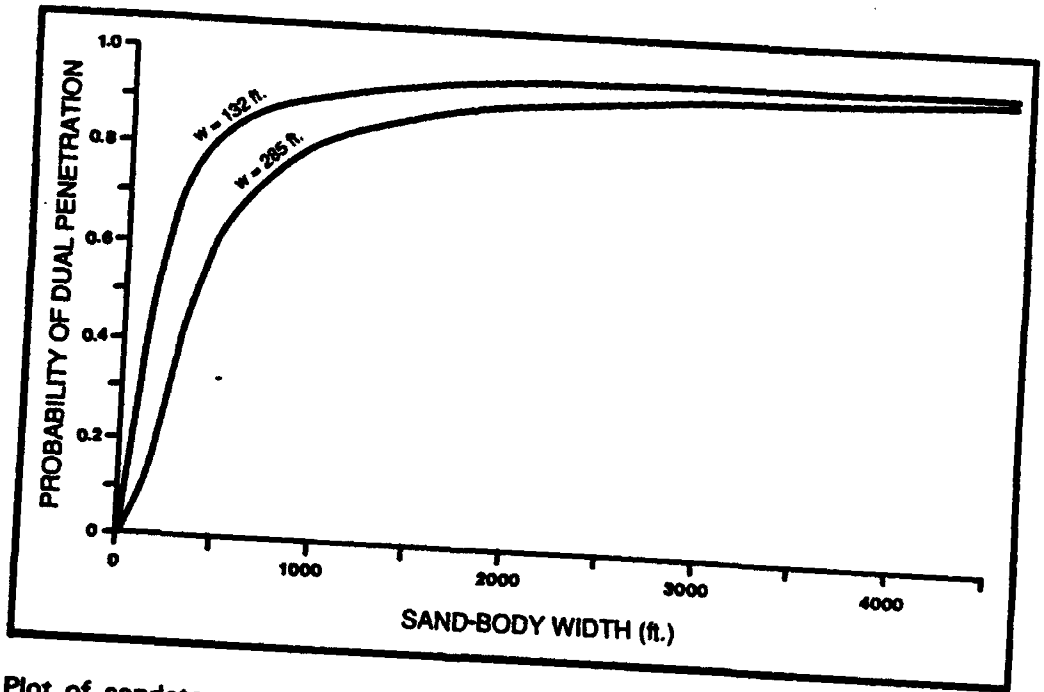
Probability of Dual Penetration											
Data Point Spacing, ft	Sand body (meander belt) width, ft										
	50	100	250	500	750	1,000	1,250	1,500	1,750	2,000	2,500
250	.064	.129	.363	.682	.788	.841	.873	.894	.909	.921	.937
500	.032	.064	.163	.363	.576	.682	.745	.788	.818	.841	.873
1,000	.016	.032	.080	.163	.253	.363	.491	.576	.636	.682	.745
1,500	.011	.021	.053	.107	.163	.221	.285	.363	.454	.523	.618
2,000	.008	.016	.040	.080	.121	.163	.206	.253	.303	.363	.491
2,500	.006	.013	.032	.064	.096	.129	.163	.197	.234	.272	.363
3,000	.005	.011	.027	.053	.080	.107	.135	.163	.192	.221	.285
3,500	.005	.009	.023	.046	.068	.092	.115	.139	.163	.187	.239
4,000	.004	.008	.020	.040	.060	.080	.100	.121	.142	.163	.206
4,500	.004	.007	.018	.035	.053	.071	.089	.107	.125	.144	.182
5,000	.003	.006	.016	.032	.048	.064	.080	.096	.113	.129	.163
6,000	.003	.005	.013	.027	.040	.053	.067	.080	.094	.107	.135
7,000	.002	.005	.011	.023	.034	.046	.057	.068	.080	.092	.115
8,000	.002	.004	.010	.020	.030	.040	.050	.060	.070	.080	.100
9,000	.002	.004	.009	.018	.027	.035	.044	.053	.062	.071	.089
10,000	.002	.003	.008	.016	.024	.032	.040	.048	.056	.064	.080
15,000	.001	.002	.005	.011	.016	.021	.027	.032	.037	.043	.053
20,000		.002	.004	.008	.012	.016	.020	.024	.028	.032	.040
25,000		.001	.003	.006	.010	.013	.016	.019	.022	.025	.032
30,000		.001	.003	.005	.008	.011	.013	.016	.019	.021	.027

Probability of Dual Penetration								
Data Point Spacing, ft	Sand body (meander belt) width, ft							
	3,000	3,500	4,000	5,000	7,500	10,000	20,000	30,000
250	.947	.954	.960	.968	.979	.984	.992	.994
500	.894	.909	.921	.937	.958	.968	.984	.989
1,000	.788	.818	.841	.873	.915	.937	.968	.979
1,500	.682	.727	.761	.809	.873	.904	.952	.968
2,000	.576	.636	.682	.745	.830	.873	.937	.958
2,500	.469	.545	.602	.682	.788	.841	.921	.947
3,000	.363	.454	.523	.618	.745	.809	.904	.937
3,500	.295	.363	.443	.554	.703	.777	.889	.926
4,000	.253	.303	.363	.491	.660	.745	.873	.915
4,500	.221	.263	.309	.427	.618	.713	.857	.904
5,000	.197	.234	.272	.363	.576	.682	.841	.894
6,000	.163	.192	.221	.285	.491	.618	.809	.873
7,000	.139	.163	.187	.239	.406	.554	.777	.851
8,000	.121	.142	.163	.206	.331	.491	.745	.830
9,000	.107	.125	.144	.182	.285	.427	.713	.809
10,000	.096	.113	.129	.163	.253	.363	.682	.788
15,000	.064	.075	.085	.107	.163	.221	.523	.682
20,000	.048	.056	.064	.080	.121	.163	.363	.576
25,000	.038	.045	.051	.064	.096	.129	.272	.469
30,000	.032	.037	.043	.053	.080	.107	.221	.363

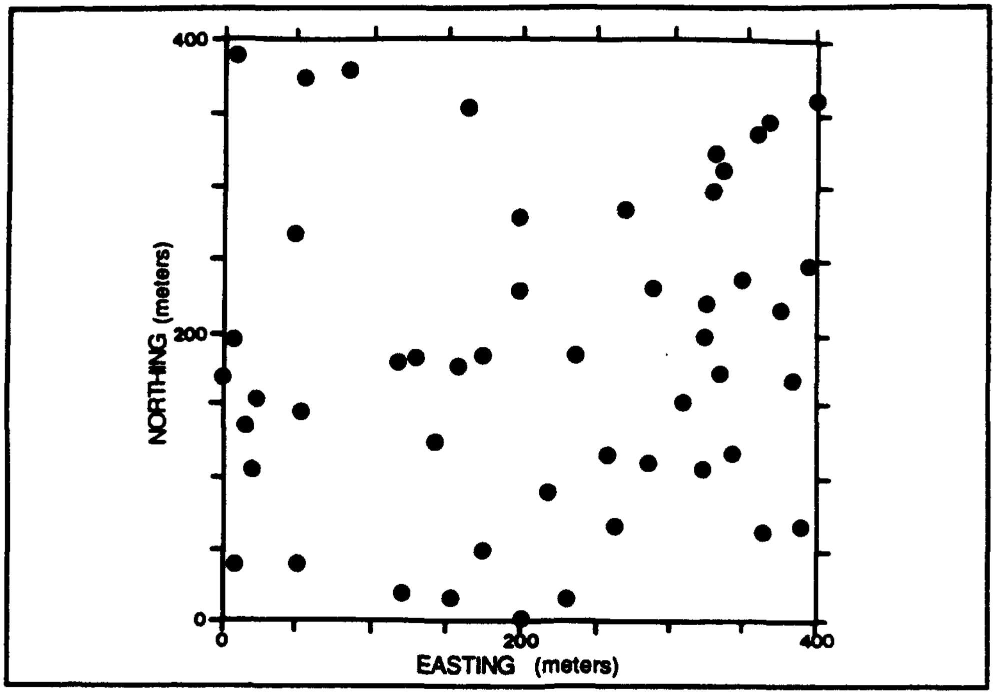
Appendix C
Software Verifications



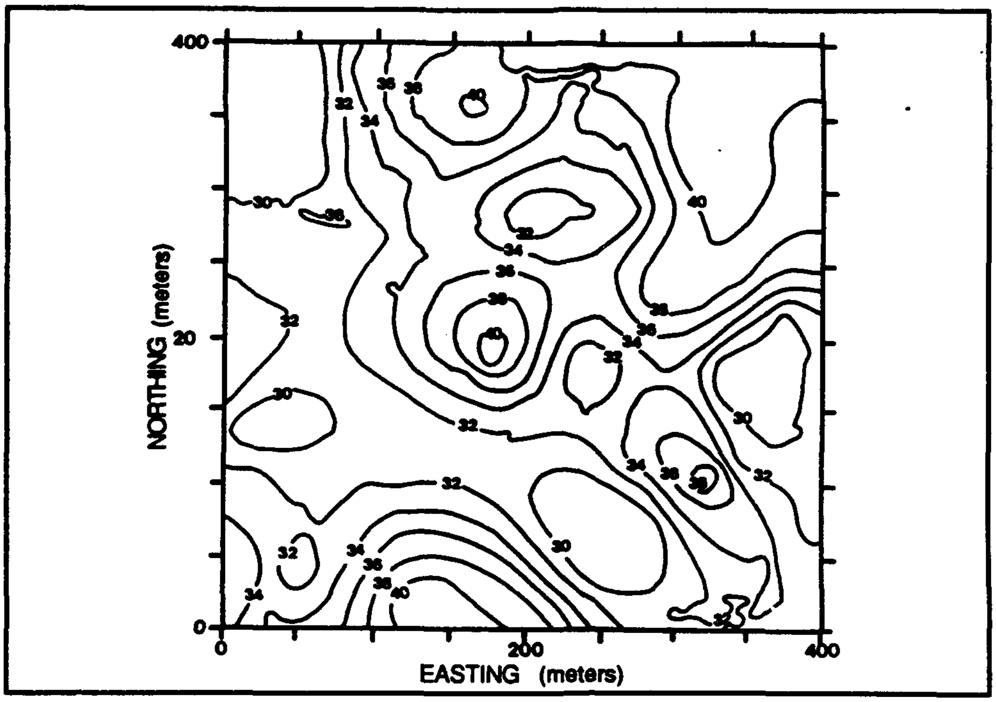
Plot of sand body meander belt width (W_m) vs. Probability of the sand body being penetrated by both wells, for selected well spacings (w) (from May 1985)



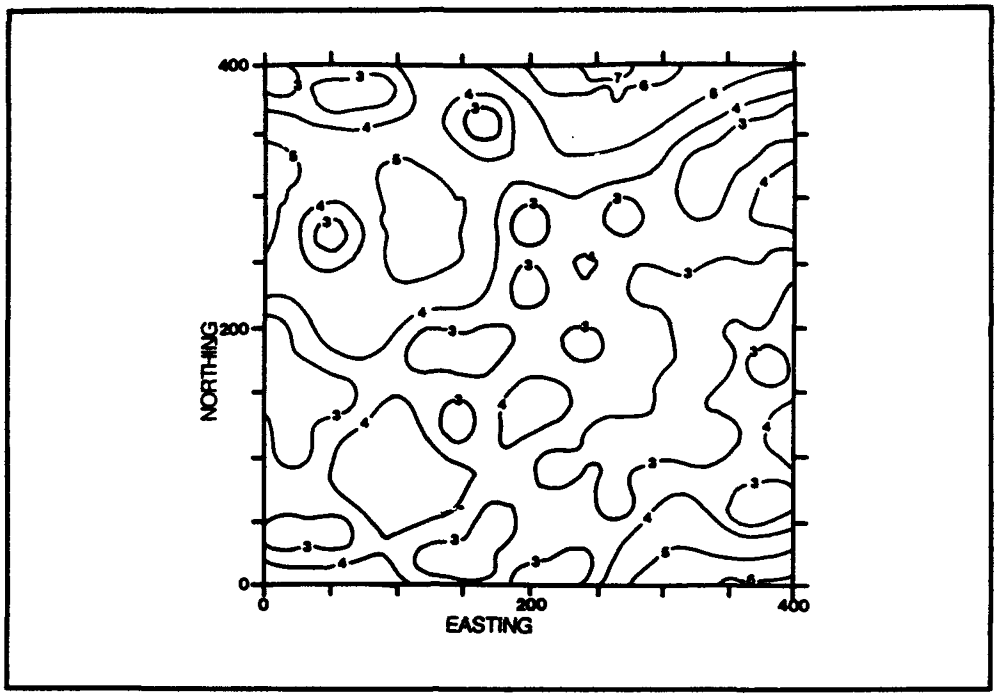
Plot of sandstone meander belt width (W_m) vs. the probability of its penetration by both wells, for well spacing (w) of 132 ft and 285 ft (after Lorenz et al. 1985)



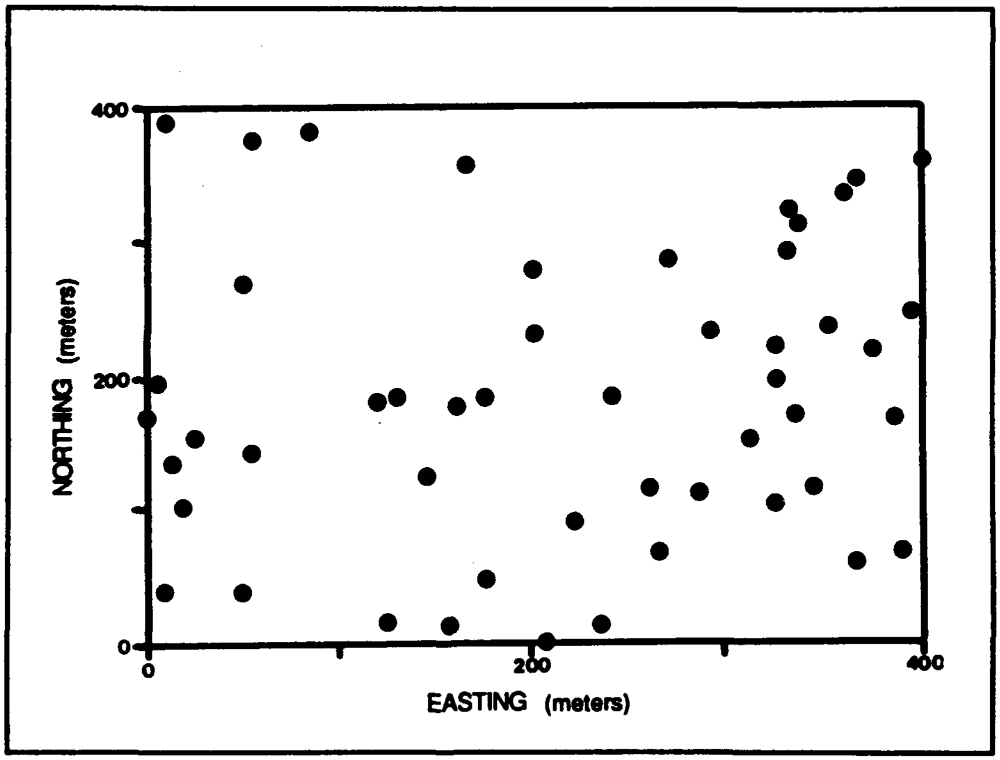
Data point locations of a simulated iron ore deposit (after Clark 1979)



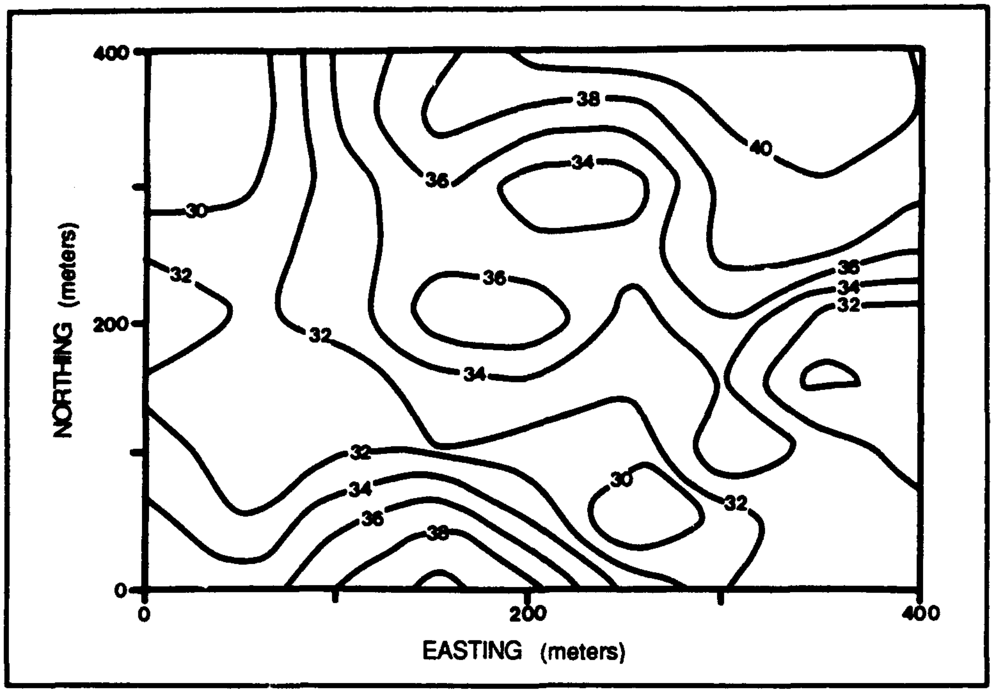
Contour of percent iron kriged from a simulated iron ore deposit data (after Clark 1979)



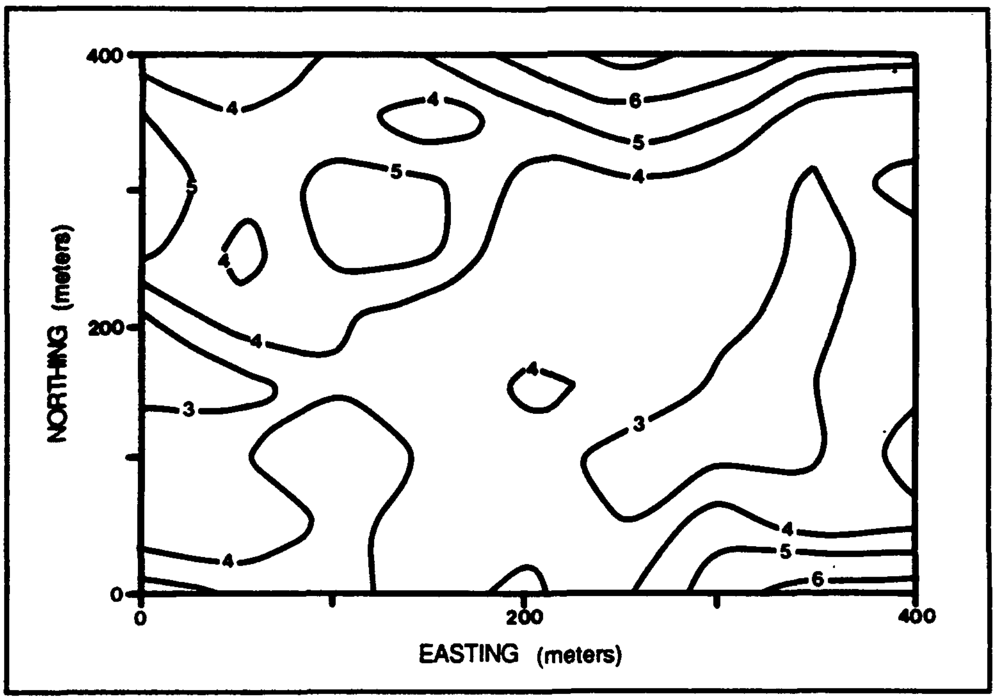
Contour of standard deviation of the kriged estimates of percent iron from a simulated iron ore deposit (after Clark 1979)



Data point locations of Clark's simulated iron ore deposit using Geo-Eas



Contour of percent iron kriged using Geo-Eas, with Clark's simulated iron ore deposit data



Contour of standard deviation of the kriging estimates of percent iron using Geo-Eas, with Clark's simulated iron ore deposit data

Appendix D
Sample Calculations

Sand Body Width Estimation

The measured thickness of 19.0 ft is multiplied by 1.1 to compensate for compaction.

$$19.0\,ft \; X \; 1.1 = 20.9\,ft$$

The 20.9 ft is then converted to meters by multiplying by 3.048 X 10^{-1} m/ft.

$$20.9\,ft \; X \; (3.048 \; X \; 10^{-1}\; m/ft) = 6.37\; m$$

This 6.37 meters is then inserted into Leeder's formula for calculating channel width (W_c).

$$W_c = 6.8h^{1.54}$$

Where h is the thickness of 6.37 meters.

$$W_c = 6.8(6.37m)^{1.54}$$

$$W_c = 117.73\; m$$

The 117.73 meters is converted to ft by multiplying by 3.281 ft/m.

$$117.73m \; X \; 3.281\; ft/m = 386.27\; ft$$

This 386.27 ft is inserted into Lorenz et al.'s equation for calculating meander belt width (W_m)

$$W_m = 7.44 W_c^{1.01}$$

$$W_m = 7.44(386.27\ ft)^{1.01}$$

$$W_m = 3050\ ft$$

The calculated meander belt width of 3050 ft is the estimate of the sand body width.

Appendix E
Data Point Locations

Data Points for the Rational for Exploration at the Rocky Mountain Arsenal

Grid Coordinates in Feet East	North	Sand body Thickness in Feet
2178931	175779	0
2183891	175445	0
2187216	175608	0
2188353	185171	0
2188139	180921	0
2178446	179361	0
2178426	185575	0
2184000	185000	19.0
2181155	184639	0
2183065	182320	10.5
2186014	184035	0
2183045	180900	28.6
2184234	177874	10.4
2181060	178469	0
2186235	180686	0
2181205	180372	0
2181444	176282	0
2186789	178332	0

May's Data Points at the Rocky Mountain Arsenal

Grid Coordinates in Feet East	North	Sand body Thickness in Feet
2184469	177203	46.0
2183284	180386	44.0
2178561	184632	0
2183045	180900	28.6
2182621	181912	21.1
2183308	183082	0
2183527	182723	37.8
2183023	183552	0
2182572	183996	0
2184218	185348	10.0
2185102	185785	0-
2183794	185108	19.0
2184285	181477	0

All Data Points at the Rocky Mountain Arsenal

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet	Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
2184469	177203	46.0	2181155	184639	0
2183284	180386	44.0	2186014	184035	0
2183045	180900	28.6	2181060	178469	0
2182621	181912	21.1	2186235	180686	0
2183527	182723	37.8	2181205	180372	0
2184218	185348	1.0	2186789	178332	0
2183794	185108	19.0	2178561	184632	0
2183841	179243	38.9	2183308	183082	0
2183065	182329	10.5	2183023	183552	0
2184127	185118	6.0	2182572	183996	0
2184378	184870	5.5	2185102	185785	0
2184128	184868	16.3	2184285	181477	0
2183878	184867	4.8	2183928	184867	5.8
2183880	184617	9.2	2183877	185067	15.0
2184130	184618	9.1	2184127	185018	14.0
2184380	184620	3.1	2183894	182367	27.4
2183780	184666	6.2	2183893	182617	31.3
2178931	175779	0	2183891	182867	33.0
2183891	175445	0	2183889	183117	25.2
2187216	175608	0	2183900	181368	40.9
2188353	185171	0	2184150	184641	6.0
2188139	180921	0	2185002	181127	3.1
2178446	179361	0	2184171	180698	29.0
2178426	185575	0	2184234	177874	10.4
			2184129	184718	10.0
			2181444	176282	0

Data Points for the Rational for Exploration on the Brazos River

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
3275000	300000	80
3275000	325000	0
3275000	350000	0
3275000	375000	0
3275000	400000	0
3275000	425000	0
3275000	450000	0
3275000	475000	0
3275000	500000	0
3258000	305500	80
3242000	314500	80
3225000	325000	80
3225000	342000	80
3213000	356500	80
3208500	374000	0
3196000	361500	80
3177500	361500	0
3190000	377000	80
3183000	393000	80
3183000	411500	80
3187500	429000	0
3170000	425000	80
3160000	440000	80

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
3160000	459000	80
3167000	403000	0
3227500	375000	0
3160000	478000	0
3131000	482500	80
3100000	300000	0
3100000	325000	0
3100000	350000	0
3100000	375000	0
3100000	400000	0
3100000	425000	0
3100000	450000	0
3100000	475000	0
3100000	500000	0
3125000	300000	0
3125000	500000	80
3150000	300000	0
3150000	500000	0
3175000	300000	0
3175000	500000	0
3200000	275000	0
3200000	300000	0
3200000	500000	0
3225000	275000	0
3225000	500000	0
3250000	275000	0
3250000	500000	0
3275000	275000	0

Data Points for the Grid Method of Exploration on the Brazos River

Grid Coordinates in Feet		Sand body Thickness in Feet	Grid Coordinates in Feet		Sand body Thickness in Feet
East	North		East	North	
3100000	300000	0	3175000	425000	80
3100000	325000	0	3175000	450000	80
3100000	350000	0	3175000	475000	0
3100000	375000	0	3175000	500000	0
3100000	400000	0	3200000	275000	0
3100000	425000	0	3200000	325000	0
3100000	450000	0	3200000	350000	80
3100000	475000	0	3200000	375000	80
3100000	500000	0	3200000	400000	0
3125000	300000	0	3200000	425000	0
3125000	450000	0	3200000	450000	0
3125000	475000	0	3200000	500000	0
3125000	500000	80	3225000	275000	0
3150000	300000	0	3225000	300000	0
3150000	400000	0	3225000	325000	80
3150000	425000	0	3225000	350000	80
3150000	450000	80	3225000	375000	0
3150000	475000	80	3225000	500000	0
3150000	500000	0	3250000	275000	0
3175000	300000	0	3250000	300000	80
3175000	350000	0	3250000	325000	80
3175000	375000	0	3250000	350000	0
3175000	400000	80	3250000	500000	0
			3275000	275000	0
			3275000	300000	80
			3275000	325000	0
			3275000	350000	0
			3275000	375000	0
			3275000	400000	0
			3275000	425000	0
			3275000	450000	0
			3275000	475000	0
			3275000	500000	0

Data Points for the Brazos River
10,000 ft Grid

Grid Coordinates in Feet		Sand body Thickness in Feet	Grid Coordinates in Feet		Sand body Thickness in Feet
East	North		East	North	
3100000	300000	0	3110000	330000	0
3100000	310000	0	3110000	340000	0
3100000	320000	0	3110000	350000	0
3100000	330000	0	3110000	360000	0
3100000	340000	0	3110000	370000	0
3100000	350000	0	3110000	380000	0
3100000	360000	0	3110000	390000	0
3100000	370000	0	3110000	400000	0
3100000	380000	0	3110000	410000	0
3100000	390000	0	3110000	420000	0
3100000	400000	0	3110000	430000	0
3100000	410000	0	3110000	440000	0
3100000	420000	0	3110000	450000	0
3100000	430000	0	3110000	460000	0
3100000	440000	0	3110000	470000	0
3100000	450000	0	3110000	480000	0
3100000	460000	0	3110000	490000	0
3100000	470000	0	3110000	500000	0
3100000	480000	0	3120000	300000	0
3100000	490000	0	3120000	310000	0
3100000	500000	0	3120000	320000	0
3110000	300000	0	3120000	330000	0
3110000	310000	0	3120000	340000	0
3110000	320000	0	3120000	350000	0
3120000	360000	0	3130000	390000	0
3120000	370000	0	3130000	400000	0
3120000	380000	0	3130000	410000	0
3120000	390000	0	3130000	420000	0
3120000	400000	0	3130000	430000	0
3120000	410000	0	3130000	440000	0
3120000	420000	0	3130000	450000	0
3120000	430000	0	3130000	460000	0
3120000	440000	0	3130000	470000	0
3120000	450000	0	3130000	480000	80
3120000	460000	0	3130000	490000	80
3120000	470000	0	3130000	500000	80
3120000	480000	0	3140000	300000	0
3120000	490000	80	3140000	310000	0
3120000	500000	80	3140000	320000	0
3130000	300000	0	3140000	330000	0
3130000	310000	0	3140000	340000	0
3130000	320000	0	3140000	350000	0
3130000	330000	0	3140000	360000	0
3130000	340000	0	3140000	370000	0
3130000	350000	0	3140000	380000	0
3130000	360000	0	3140000	390000	0

Data Points for the Brazos River
10,000 ft Grid

Grid Coordinates in Feet East	North	Sand body Thickness in Feet	Grid Coordinates in Feet East	North	Sand body Thickness in Feet
3130000	370000	0	3140000	400000	0
3130000	380000	0	3140000	410000	0
3140000	420000	0	3150000	450000	80
3140000	430000	0	3150000	460000	80
3140000	440000	0	3150000	470000	80
3140000	450000	0	3150000	480000	0
3140000	460000	80	3150000	490000	0
3140000	470000	80	3150000	500000	0
3140000	480000	80	3160000	300000	0
3140000	490000	80	3160000	310000	0
3140000	500000	80	3160000	320000	0
3150000	300000	0	3160000	330000	0
3150000	310000	0	3160000	340000	0
3150000	320000	0	3160000	350000	0
3150000	330000	0	3160000	360000	0
3150000	340000	0	3160000	370000	0
3150000	350000	0	3160000	380000	0
3150000	360000	0	3160000	390000	0
3150000	370000	0	3160000	400000	0
3150000	380000	0	3160000	410000	0
3150000	390000	0	3160000	420000	0
3150000	400000	0	3160000	430000	0
3150000	410000	0	3160000	440000	80
3150000	420000	0	3160000	450000	80
3150000	430000	0	3160000	460000	80
3150000	440000	0	3160000	470000	80
3160000	480000	0	3180000	300000	0
3160000	490000	0	3180000	310000	0
3160000	500000	0	3180000	320000	0
3170000	300000	0	3180000	330000	0
3170000	310000	0	3180000	340000	0
3170000	320000	0	3180000	350000	0
3170000	330000	0	3180000	360000	0
3170000	340000	0	3180000	370000	0
3170000	350000	0	3180000	380000	80
3170000	360000	0	3180000	390000	80
3170000	370000	0	3180000	400000	80
3170000	380000	0	3180000	410000	80
3170000	390000	0	3180000	420000	80
3170000	400000	0	3180000	430000	80
3170000	410000	80	3180000	440000	80
3170000	420000	80	3180000	450000	0
3170000	430000	80	3180000	460000	0
3170000	440000	80	3180000	470000	0
3170000	450000	80	3180000	480000	0
3170000	460000	0	3180000	490000	0
3170000	470000	0	3180000	500000	0

Data Points for the Brazos River
10,000 ft Grid

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
3170000	480000	0
3170000	490000	0
3170000	500000	0
3190000	330000	0
3190000	340000	0
3190000	350000	0
3190000	360000	80
3190000	370000	80
3190000	380000	30
3190000	390000	80
3190000	400000	80
3190000	410000	80
3190000	420000	80
3190000	430000	0
3190000	440000	0
3190000	450000	0
3190000	460000	0
3190000	470000	0
3190000	480000	0
3190000	490000	0
3190000	500000	0
3200000	280000	0
3200000	290000	0
3200000	300000	0
3200000	310000	0
3200000	320000	0
3200000	330000	0
3210000	350000	80
3210000	360000	80
3210000	370000	0
3210000	380000	0
3210000	390000	0
3210000	400000	0
3210000	410000	0
3210000	420000	0
3210000	430000	0
3210000	440000	0
3210000	450000	0
3210000	460000	0
3210000	470000	0
3210000	480000	0
3210000	490000	0
3210000	500000	0
3220000	280000	0
3220000	290000	0
3220000	300000	0
3220000	310000	0
3190000	300000	0
3190000	310000	0
3190000	320000	0
3200000	340000	80
3200000	350000	80
3200000	360000	80
3200000	370000	80
3200000	380000	0
3200000	390000	0
3200000	400000	0
3200000	410000	0
3200000	420000	0
3200000	430000	0
3200000	440000	0
3200000	450000	0
3200000	460000	0
3200000	470000	0
3200000	480000	0
3200000	490000	0
3200000	500000	0
3210000	280000	0
3210000	290000	0
3210000	300000	0
3210000	310000	0
3210000	320000	0
3210000	330000	80
3210000	340000	80
3220000	360000	80
3220000	370000	0
3220000	380000	0
3220000	390000	0
3220000	400000	0
3220000	410000	0
3220000	420000	0
3220000	430000	0
3220000	440000	0
3220000	450000	0
3220000	460000	0
3220000	470000	0
3220000	480000	0
3220000	490000	0
3220000	500000	0
3230000	280000	0
3230000	290000	0
3230000	300000	0
3230000	310000	0
3230000	320000	80

Data Points for the Brazos River
10,000 ft Grid

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
3220000	320000	80
3220000	330000	80
3220000	340000	80
3220000	350000	80
3230000	370000	0
3230000	380000	0
3230000	390000	0
3230000	400000	0
3230000	410000	0
3230000	420000	0
3230000	430000	0
3230000	440000	0
3230000	450000	0
3230000	460000	0
3230000	470000	0
3230000	480000	0
3230000	490000	0
3230000	500000	0
3240000	280000	0
3240000	290000	0
3240000	300000	80
3240000	310000	80
3240000	320000	80
3240000	330000	80
3240000	340000	80
3240000	350000	0
3240000	360000	0
3240000	370000	0
3250000	390000	0
3250000	400000	0
3250000	410000	0
3250000	420000	0
3250000	430000	0
3250000	440000	0
3250000	450000	0
3250000	460000	0
3250000	470000	0
3250000	480000	0
3250000	490000	0
3250000	500000	0
3260000	280000	0
3260000	290000	0
3260000	300000	80
3260000	310000	80
3260000	320000	0
3260000	330000	0
3260000	340000	0

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
3230000	330000	80
3230000	340000	80
3230000	350000	0
3230000	360000	0
3240000	380000	0
3240000	390000	0
3240000	400000	0
3240000	410000	0
3240000	420000	0
3240000	430000	0
3240000	440000	0
3240000	450000	0
3240000	460000	0
3240000	470000	0
3240000	480000	0
3240000	490000	0
3240000	500000	0
3250000	280000	0
3250000	290000	0
3250000	300000	80
3250000	310000	80
3250000	320000	80
3250000	330000	80
3250000	340000	0
3250000	350000	0
3250000	360000	0
3250000	370000	0
3250000	380000	0
3260000	400000	0
3260000	410000	0
3260000	420000	0
3260000	430000	0
3260000	440000	0
3260000	450000	0
3260000	460000	0
3260000	470000	0
3260000	480000	0
3260000	490000	0
3260000	500000	0
3270000	280000	0
3270000	290000	80
3270000	300000	80
3270000	310000	80
3270000	320000	0
3270000	330000	0
3270000	340000	0
3270000	350000	0

Data Points for the Brazos River
10,000 ft Grid

Grid Coordinates in Feet East	North	Sand body Thickness in Feet	Grid Coordinates in Feet East	North	Sand body Thickness in Feet
3260000	350000	0	3270000	360000	0
3260000	360000	0	3270000	370000	0
3260000	370000	0	3270000	380000	0
3260000	380000	0	3270000	390000	0
3260000	390000	0	3270000	400000	0
3270000	410000	0	3280000	420000	0
3270000	420000	0	3280000	430000	0
3270000	430000	0	3280000	440000	0
3270000	440000	0	3280000	450000	0
3270000	450000	0	3280000	460000	0
3270000	460000	0	3280000	470000	0
3270000	470000	0	3280000	480000	0
3270000	480000	0	3280000	490000	0
3270000	490000	0	3280000	500000	0
3270000	500000	0			
3280000	280000	0			
3280000	290000	80			
3280000	300000	80			
3280000	310000	0			
3280000	320000	0			
3280000	330000	0			
3280000	340000	0			
3280000	350000	0			
3280000	360000	0			
3280000	370000	0			
3280000	380000	0			
3280000	390000	0			
3280000	400000	0			
3280000	410000	0			

Data Points for the Salt River 1,000 ft Grid

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet	Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
435000	875000	17.5	437000	877000	17.5
435000	876000	17.5	437000	878000	17.5
435000	877000	17.5	437000	879000	0
435000	878000	17.5	437000	880000	0
435000	879000	0	437000	881000	0
435000	880000	0	437000	882000	0
435000	881000	0	437000	883000	0
435000	882000	0	437000	884000	0
435000	883000	0	437000	885000	0
435000	884000	0	438000	875000	0
435000	885000	0	438000	876000	17.5
436000	875000	0	438000	877000	17.5
436000	876000	17.5	438000	878000	17.5
436000	877000	17.5	438000	879000	0
436000	878000	17.5	438000	880000	0
436000	879000	0	438000	881000	0
436000	880000	0	438000	882000	0
436000	881000	0	438000	883000	0
436000	882000	0	438000	884000	0
436000	883000	0	438000	885000	0
436000	884000	0	439000	875000	0
436000	885000	0	439000	876000	0
437000	875000	0	439000	877000	17.5
437000	876000	17.5	439000	878000	17.5
439000	879000	0	441000	881000	0
439000	880000	0	441000	882000	0
439000	881000	0	441000	883000	0
439000	882000	0	441000	884000	0
439000	883000	0	441000	885000	0
439000	884000	0	442000	875000	0
439000	885000	0	442000	876000	0
440000	875000	0	442000	877000	17.5
440000	876000	0	442000	878000	17.5
440000	877000	17.5	442000	879000	0
440000	878000	17.5	442000	880000	0
440000	879000	0	442000	881000	0
440000	880000	0	442000	882000	0
440000	881000	0	442000	883000	0
440000	882000	0	442000	884000	0
440000	883000	0	442000	885000	0
440000	884000	0	443000	875000	0
440000	885000	0	443000	876000	0
441000	875000	0	443000	877000	17.5
441000	876000	0	443000	878000	17.5
441000	877000	17.5	443000	879000	0
441000	878000	17.5	443000	880000	0
441000	879000	0	443000	881000	0

Data Points for the Salt River 1,000 ft Grid

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
441000	880000	0
443000	883000	0
443000	884000	0
443000	885000	0
444000	875000	0
444000	876000	0
444000	877000	17.5
444000	878000	17.5
451000	877000	0
444000	879000	0
444000	880000	0
444000	881000	0
444000	882000	0
444000	883000	0
444000	884000	0
444000	885000	0
445000	875000	0
445000	876000	0
445000	877000	17.5
445000	878000	17.5
445000	879000	0
445000	880000	0
445000	881000	0
445000	882000	0
445000	883000	0
448000	875000	0
448000	876000	0
448000	877000	0
448000	878000	17.5
448000	879000	17.5
448000	880000	0
448000	881000	0
448000	882000	0
448000	883000	0
448000	884000	0
448000	885000	0
449000	875000	0
449000	876000	0
449000	877000	0
449000	878000	17.5
449000	879000	17.5
449000	800000	17.5
449000	810000	0
449000	882000	0
449000	883000	0
449000	884000	0
449000	885000	0

Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
443000	882000	0
445000	884000	0
445000	885000	0
446000	875000	0
446000	876000	0
446000	877000	17.5
446000	878000	17.5
446000	879000	17.5
446000	880000	0
446000	881000	0
446000	882000	0
446000	883000	0
446000	884000	0
446000	885000	0
447000	875000	0
447000	876000	0
447000	877000	17.5
447000	878000	17.5
447000	879000	17.5
447000	880000	0
447000	881000	0
447000	882000	0
447000	883000	0
447000	884000	0
447000	885000	0
450000	877000	0
450000	878000	0
450000	879000	17.5
450000	880000	17.5
450000	881000	17.5
450000	882000	0
450000	883000	0
450000	884000	0
450000	885000	0
451000	875000	0
451000	876000	0
453000	878000	0
453000	879000	0
453000	880000	17.5
453000	881000	17.5
453000	882000	0
453000	883000	0
453000	884000	0
453000	885000	0
454000	875000	0
454000	876000	0
454000	877000	0

Data Points for the Salt River 1,000 ft Grid

Grid Coordinates in Feet		Sand body Thickness in Feet
East	North	
450000	875000	0
450000	876000	0
454000	880000	17.5
454000	881000	17.5
454000	882000	17.5
454000	883000	0
454000	884000	0
454000	885000	0
455000	875000	0
455000	876000	0
455000	877000	0
455000	878000	0
455000	879000	0
455000	880000	17.5
455000	881000	17.5
455000	882000	0
455000	883000	0
455000	884000	0
455000	885000	0
456000	875000	0
456000	876000	0
456000	877000	0
456000	878000	0
456000	879000	0
456000	880000	17.5
456000	881000	17.5
458000	884000	0
458000	885000	0
459000	875000	0
459000	876000	0
459000	877000	0
459000	878000	0
459000	879000	17.5
459000	880000	17.5
459000	881000	17.5
459000	882000	0
459000	883000	0
459000	884000	0
459000	885000	0
460000	875000	0
460000	876000	0
460000	877000	0
460000	878000	0
460000	879000	17.5
460000	880000	17.5
460000	881000	0
460000	882000	0
454000	878000	0
454000	879000	0
456000	882000	0
456000	883000	0
456000	884000	0
456000	885000	0
457000	875000	0
457000	876000	0
457000	877000	0
457000	878000	0
457000	879000	0
457000	880000	17.5
457000	881000	17.5
457000	882000	0
457000	883000	0
457000	884000	0
457000	885000	0
458000	875000	0
458000	876000	0
458000	877000	0
458000	878000	0
458000	879000	0
458000	880000	17.5
458000	881000	17.5
458000	882000	0
458000	883000	0
461000	875000	0
461000	876000	0
461000	877000	0
461000	878000	0
461000	879000	17.5
461000	880000	17.5
461000	881000	0
461000	882000	0
461000	883000	0
461000	884000	0
461000	885000	0
462000	875000	0
462000	876000	0
462000	877000	0
462000	878000	0
462000	879000	17.5
462000	880000	17.5
462000	881000	0
462000	882000	0
462000	883000	0
462000	884000	0

Data Points for the Salt River 1,000 ft Grid

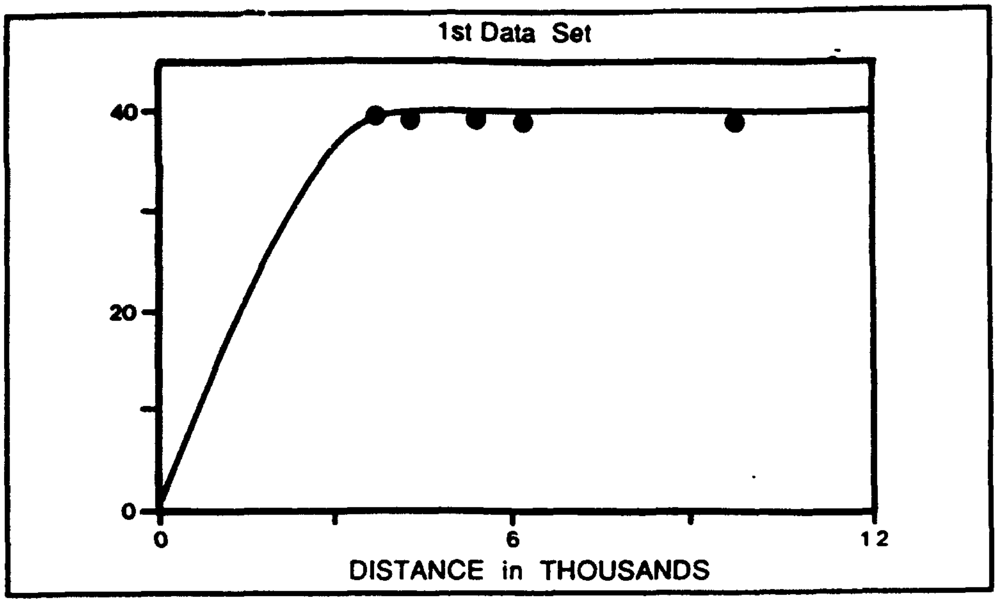
Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
460000	883000	0
460000	884000	0
460000	885000	0
463000	877000	0
463000	878000	0
463000	879000	17.5
463000	880000	17.5
463000	881000	0
463000	882000	0
463000	883000	0
463000	884000	0
463000	885000	0
464000	875000	0
464000	876000	0
464000	877000	0
464000	878000	17.5
464000	879000	17.5
464000	880000	17.5
464000	881000	0
464000	882000	0
464000	883000	0
464000	884000	0
464000	885000	0
465000	875000	0
465000	876000	0
465000	877000	0
465000	878000	17.5
467000	881000	0
467000	882000	0
467000	883000	0
467000	884000	0
467000	885000	0
468000	875000	0
468000	876000	0
468000	877000	0
468000	878000	17.5
468000	879000	17.5
468000	880000	17.5
468000	881000	0
468000	882000	0
468000	883000	0
468000	884000	0
468000	885000	0
469000	875000	0
469000	876000	0
469000	877000	0
469000	878000	0

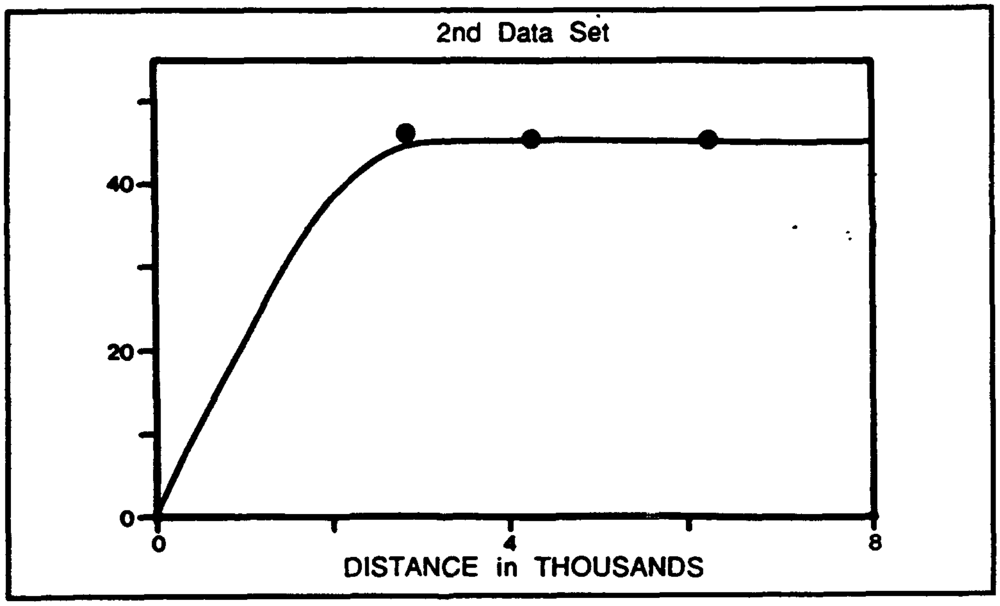
Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
462000	885000	0
463000	875000	0
463000	876000	0
465000	879000	17.5
465000	880000	17.5
465000	881000	0
465000	882000	0
465000	883000	0
465000	884000	0
465000	885000	0
466000	875000	0
466000	876000	0
466000	877000	0
466000	878000	17.5
466000	879000	17.5
466000	880000	17.5
466000	881000	0
466000	882000	0
466000	883000	0
466000	884000	0
466000	885000	0
467000	875000	0
467000	876000	0
467000	877000	0
467000	878000	17.5
467000	879000	17.5
467000	880000	17.5
469000	883000	0
469000	884000	0
469000	885000	0
470000	875000	0
470000	876000	0
470000	877000	0
470000	878000	17.5
470000	879000	17.5
470000	880000	17.5
470000	881000	17.5
470000	882000	0
470000	883000	0
470000	884000	0
470000	885000	0
471000	875000	0
471000	876000	0
471000	877000	0
471000	878000	17.5
471000	879000	17.5
471000	880000	17.5

Data Points for the Salt River 1,000 ft Grid

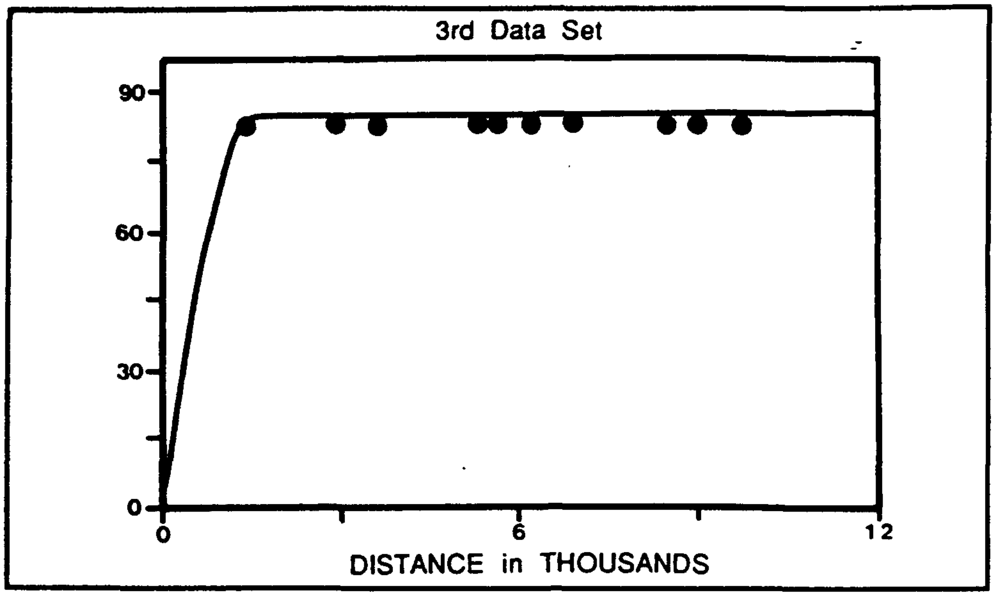
Grid Coordinates in Feet East	Grid Coordinates in Feet North	Sand body Thickness in Feet
469000	879000	17.5
469000	880000	17.5
469000	881000	17.5
469000	882000	0
471000	885000	0
472000	875000	0
472000	876000	0
472000	877000	0
472000	878000	0
472000	879000	17.5
472000	880000	17.5
472000	881000	17.5
472000	882000	17.5
472000	883000	17.5
472000	884000	0
472000	885000	0
473000	875000	0
473000	876000	0
473000	877000	0
473000	878000	0
473000	879000	17.5
473000	880000	17.5
473000	881000	17.5
473000	882000	17.5
473000	883000	17.5
473000	884000	0
473000	885000	0
474000	875000	0
451000	881000	17.5
451000	882000	0
451000	883000	0
451000	884000	0
471000	881000	17.5
471000	882000	17.5
471000	883000	0
471000	884000	0
474000	876000	0
474000	877000	0
474000	878000	0
474000	879000	0
474000	880000	17.5
474000	881000	17.5
474000	882000	17.5
474000	883000	17.5
474000	884000	0
474000	885000	0
475000	875000	0
475000	876000	0
475000	877000	0
475000	878000	0
475000	879000	0
475000	880000	0
475000	881000	17.5
475000	882000	17.5
475000	883000	17.5
475000	884000	0
475000	885000	0
451000	878000	0
451000	879000	17.5
451000	880000	17.5
451000	885000	0
452000	875000	0
452000	876000	0
452000	877000	0
452000	878000	0
452000	879000	0
452000	880000	17.5
452000	881000	17.5
452000	882000	0
452000	883000	0
452000	884000	0
452000	885000	0
453000	875000	0
453000	876000	0
453000	877000	0

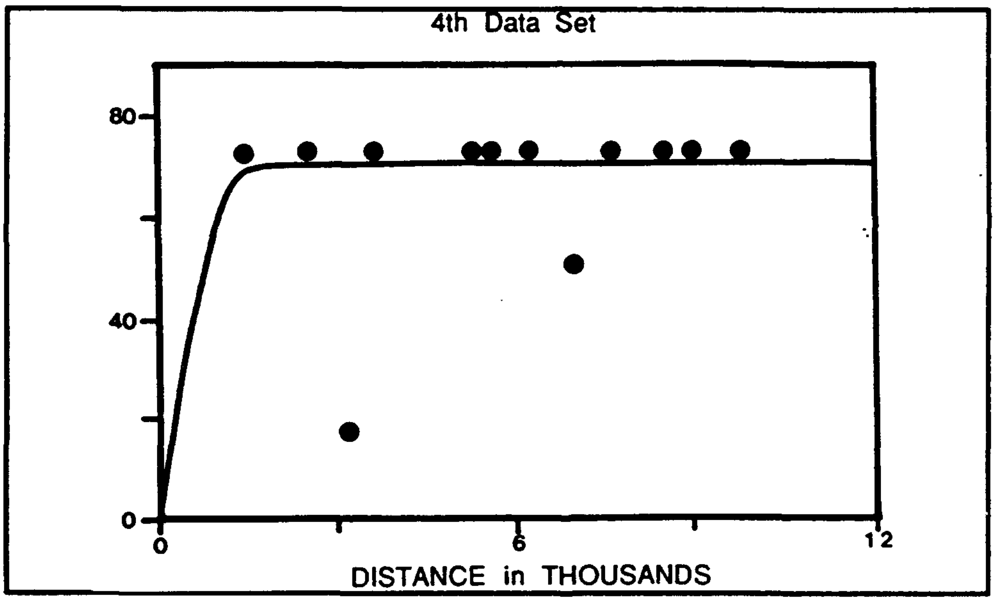
Appendix F
Variograms



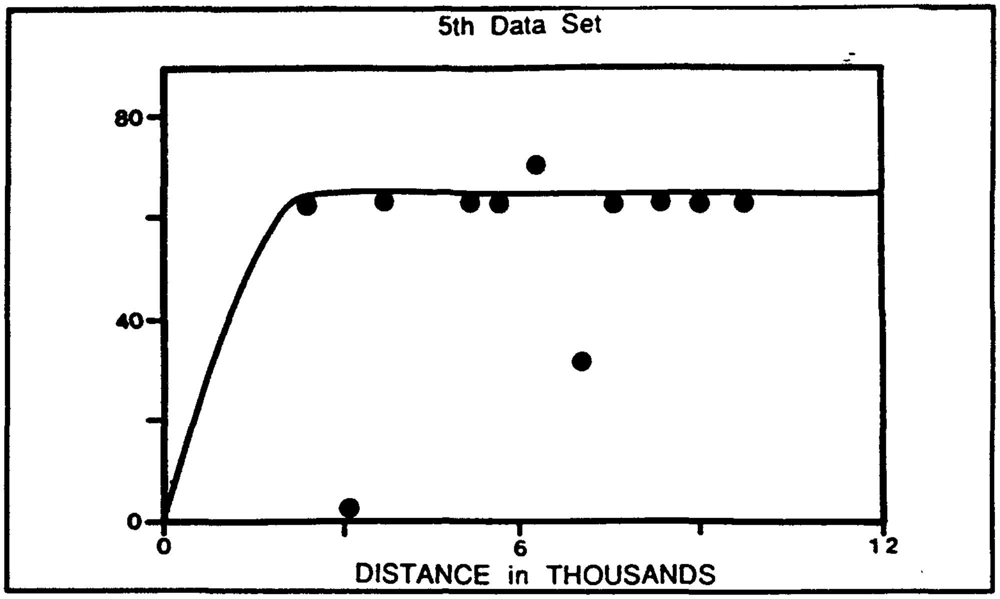


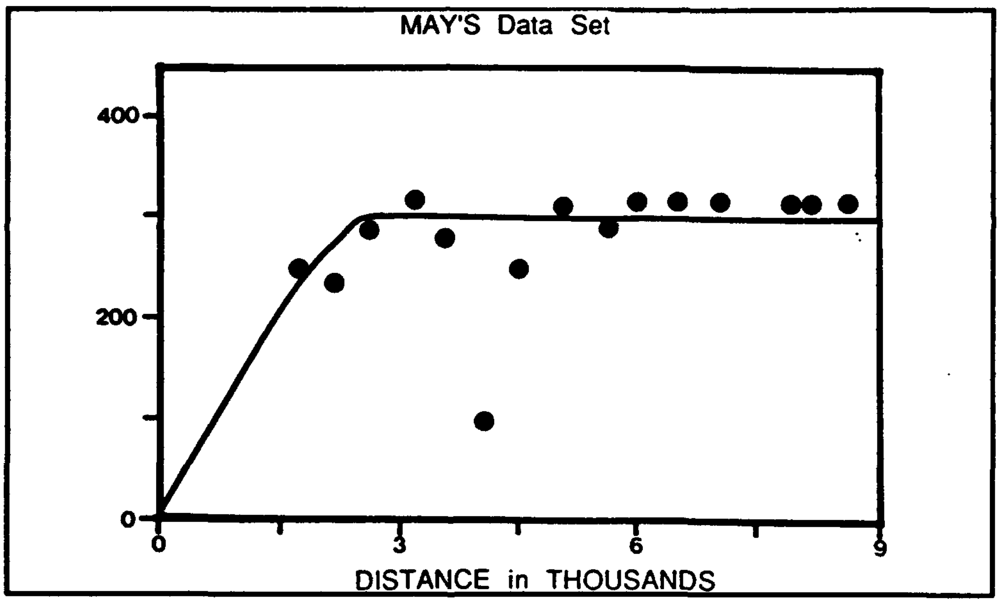
Rocky mountain arsenal



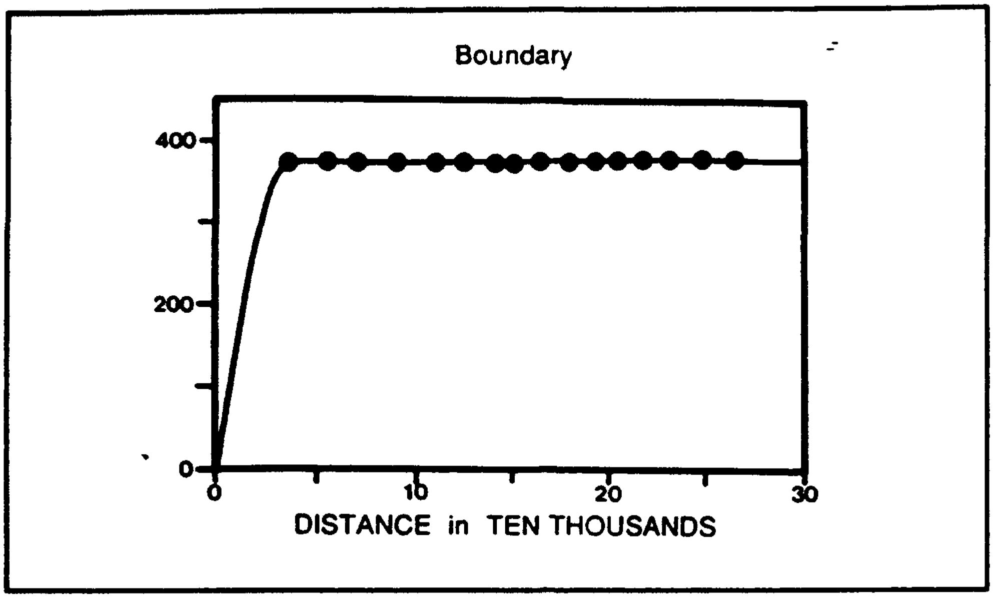


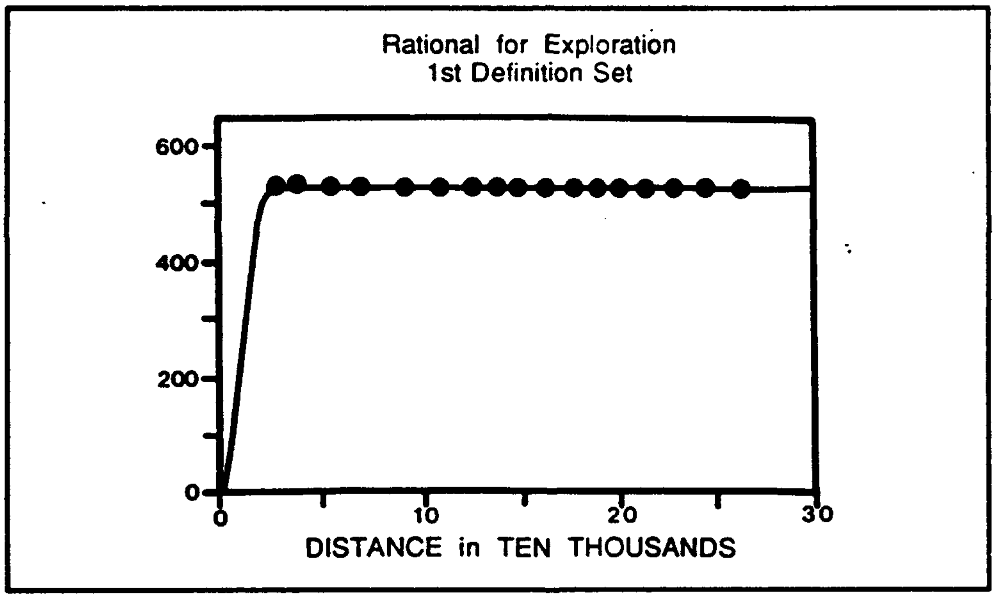
Rocky mountain arsenal



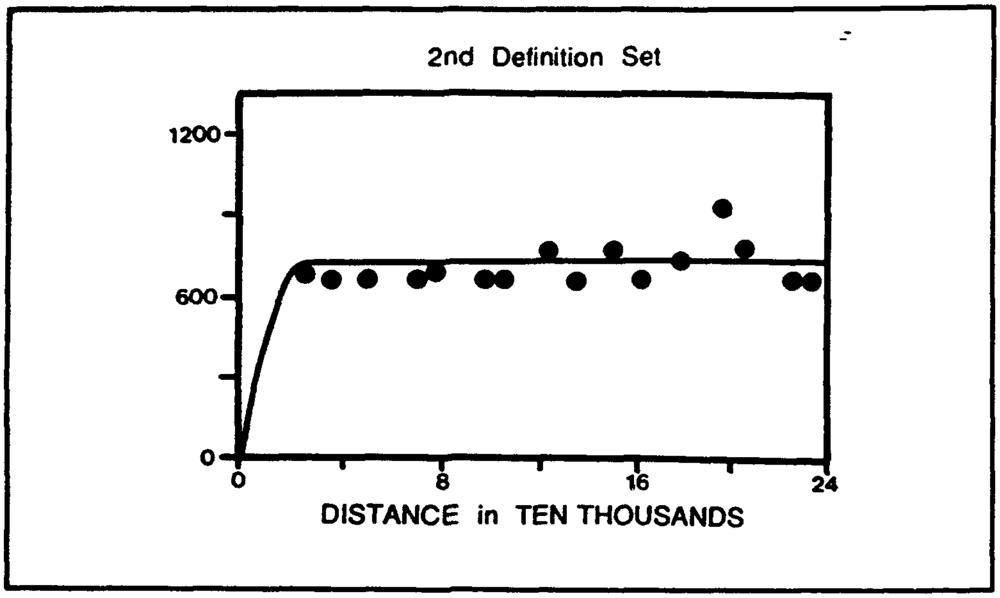


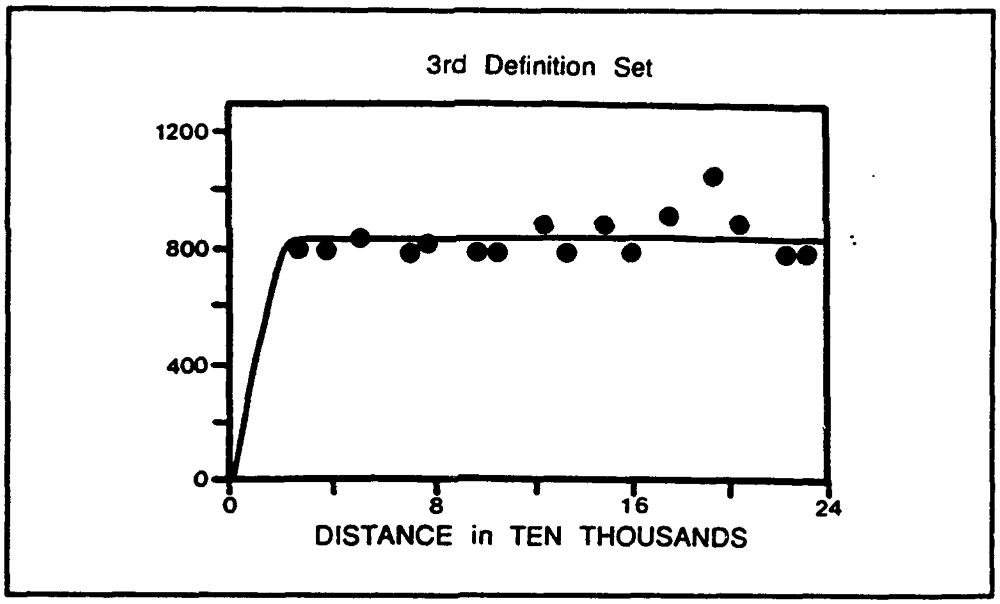
Rocky mountain arsenal



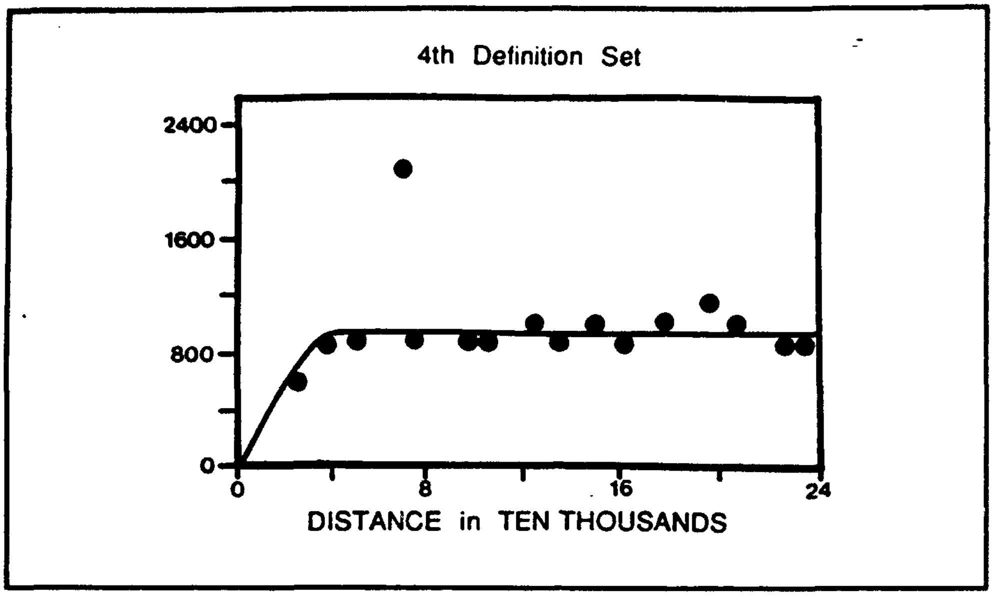


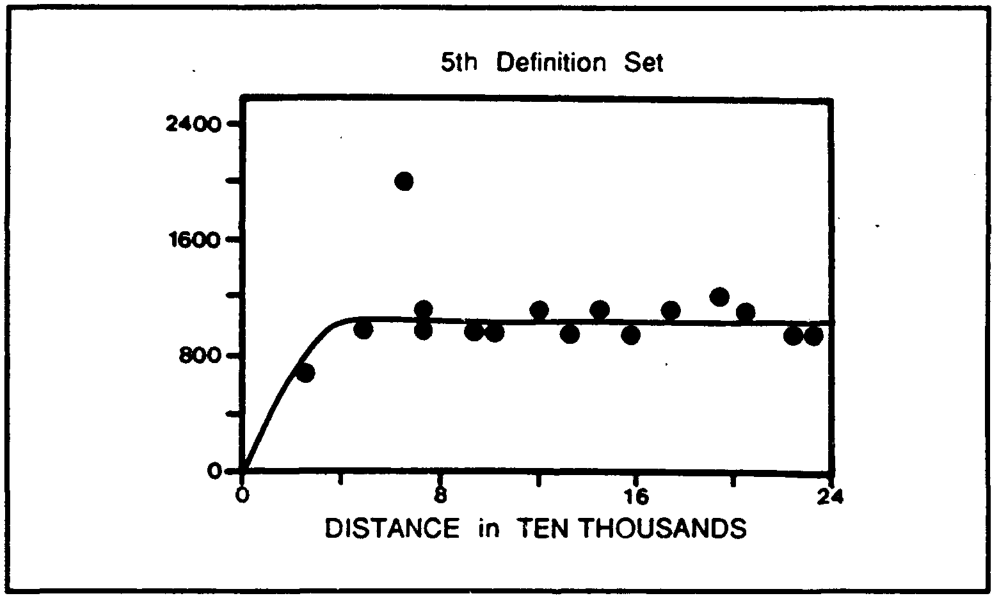
Brazos river rationale for exploration



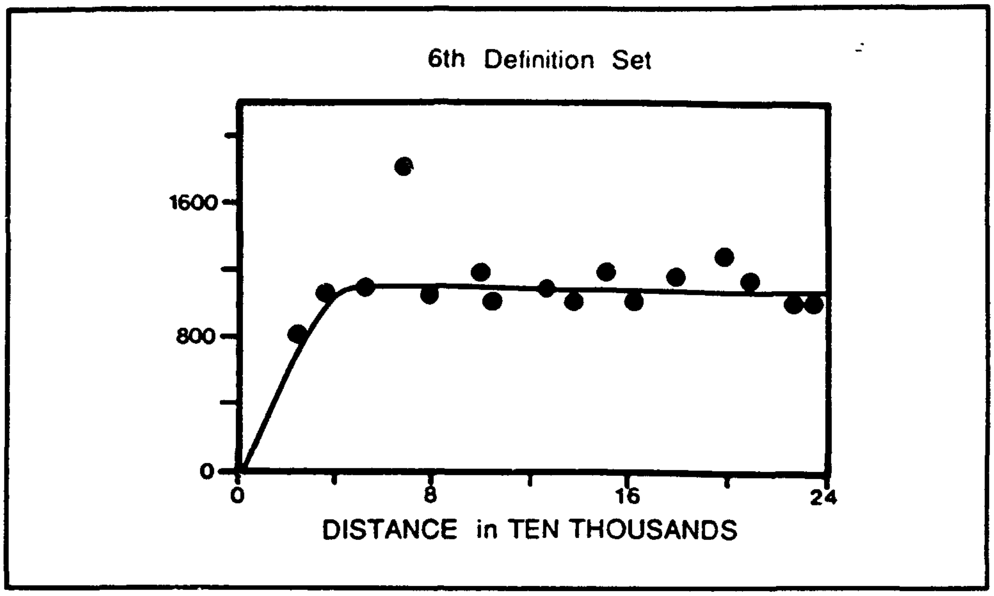


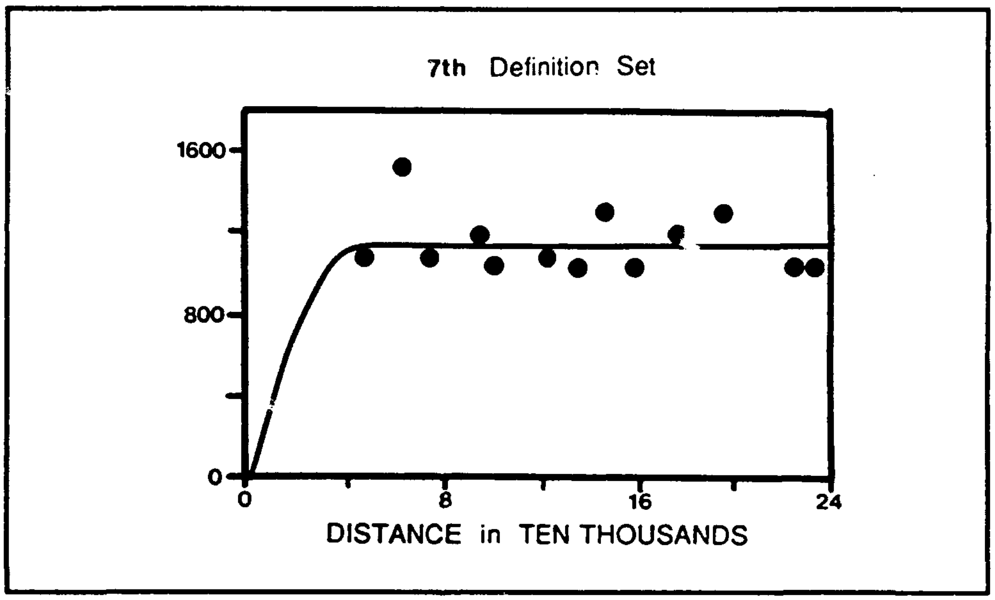
Brazos river rationale for exploration



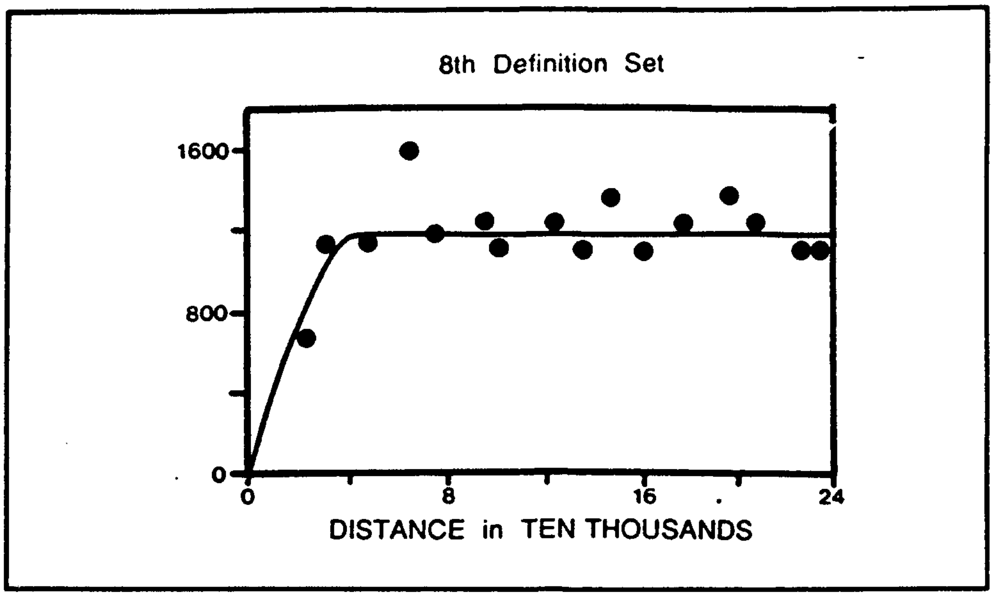


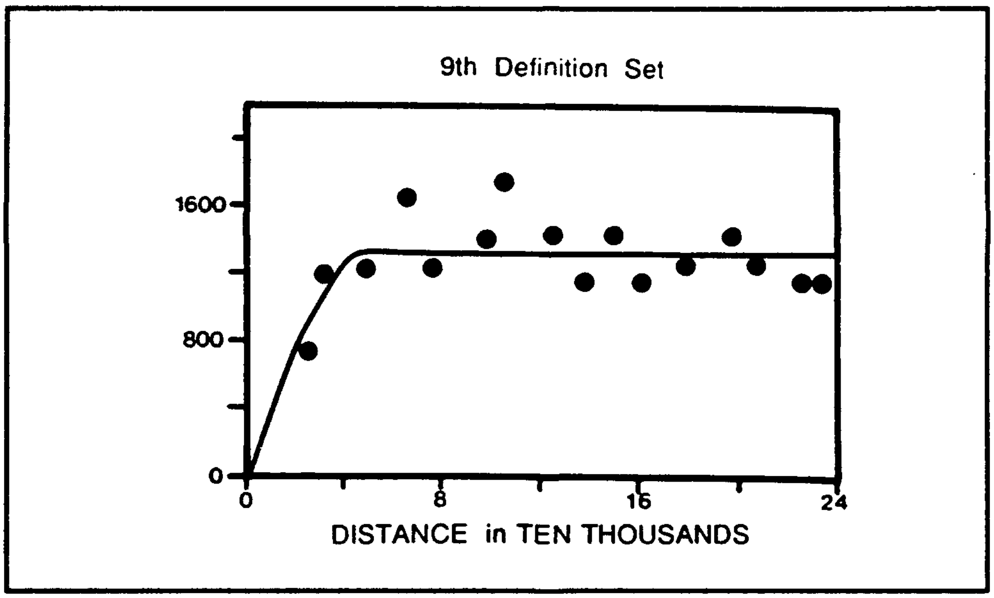
Brazos river rationale for exploration



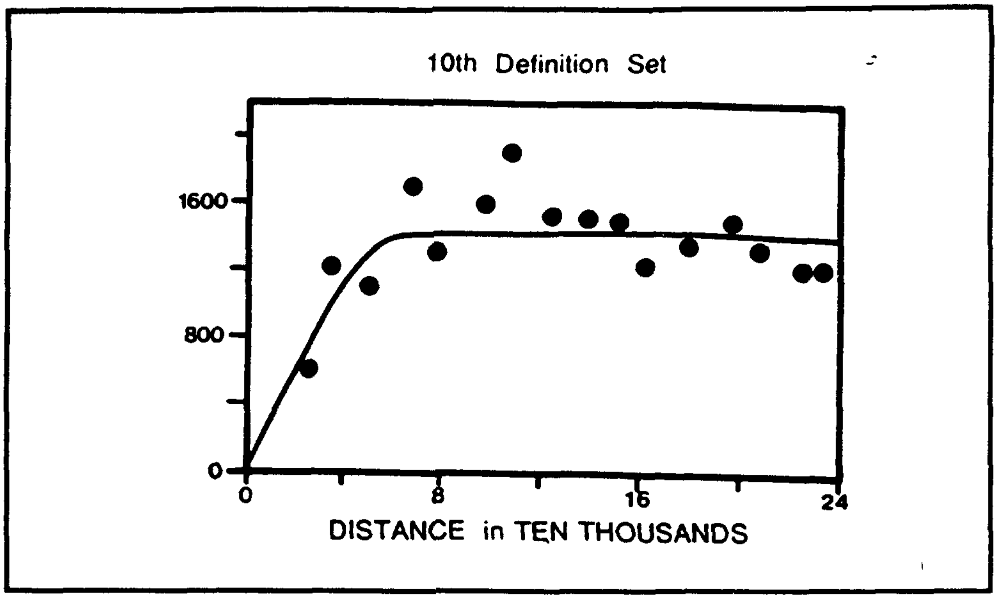


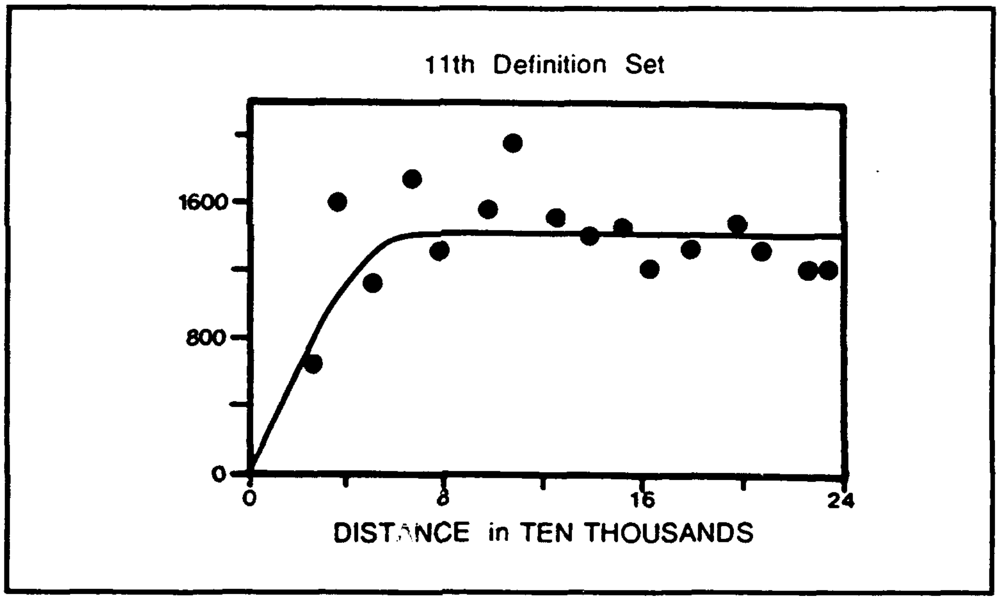
Brazos river rationale for exploration



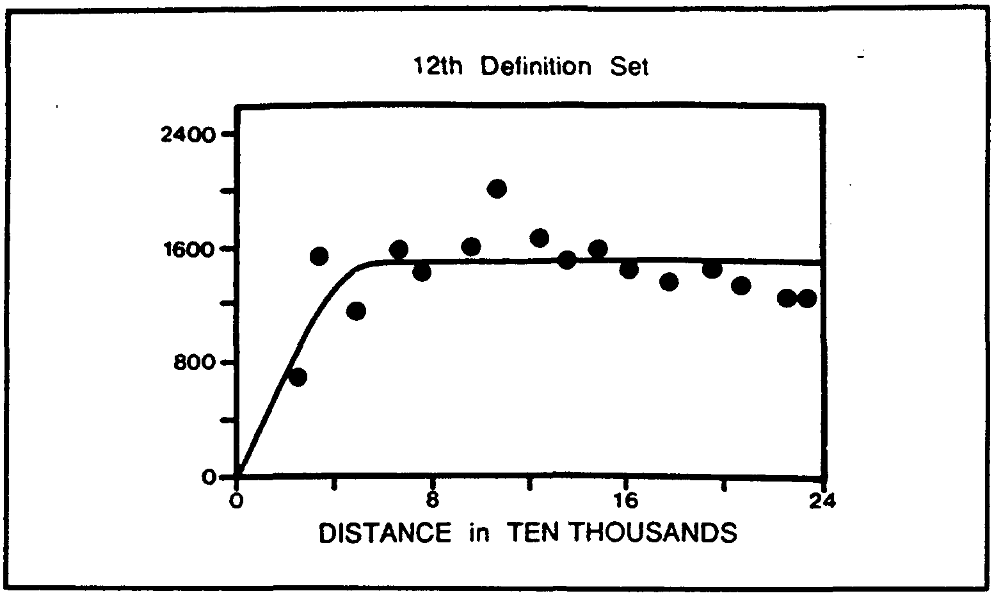


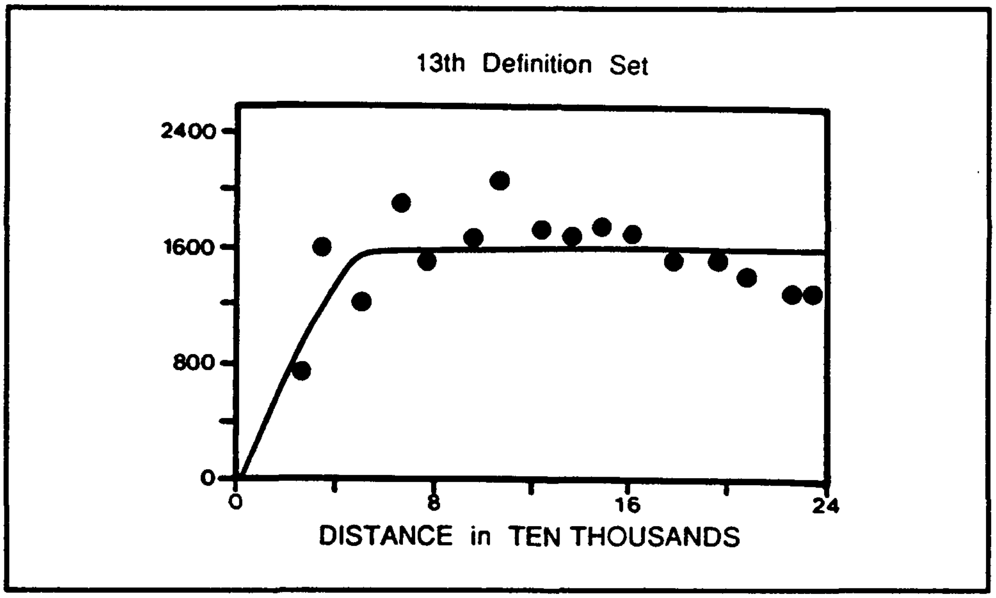
Brazos river rationale for exploration



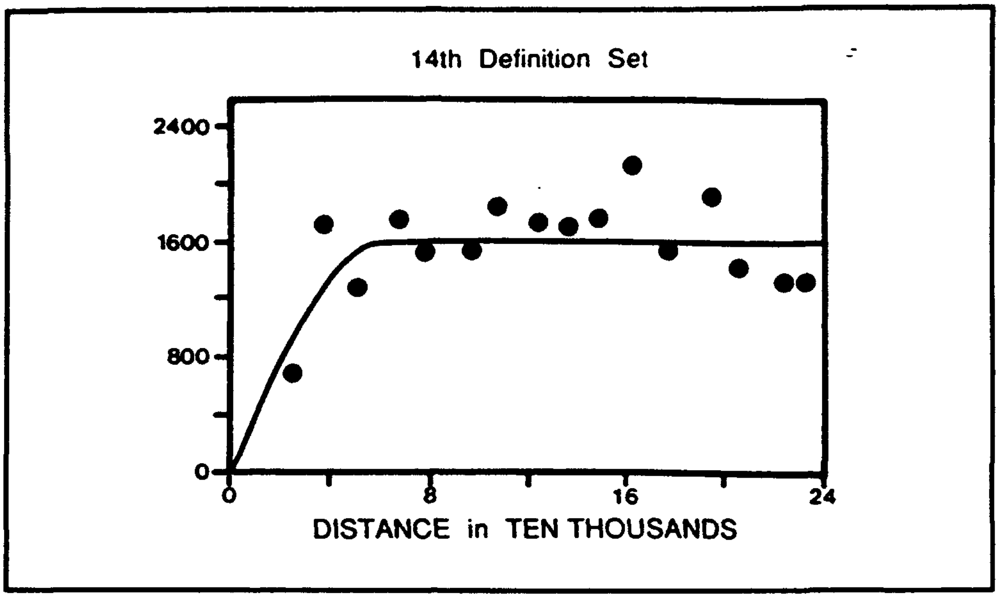


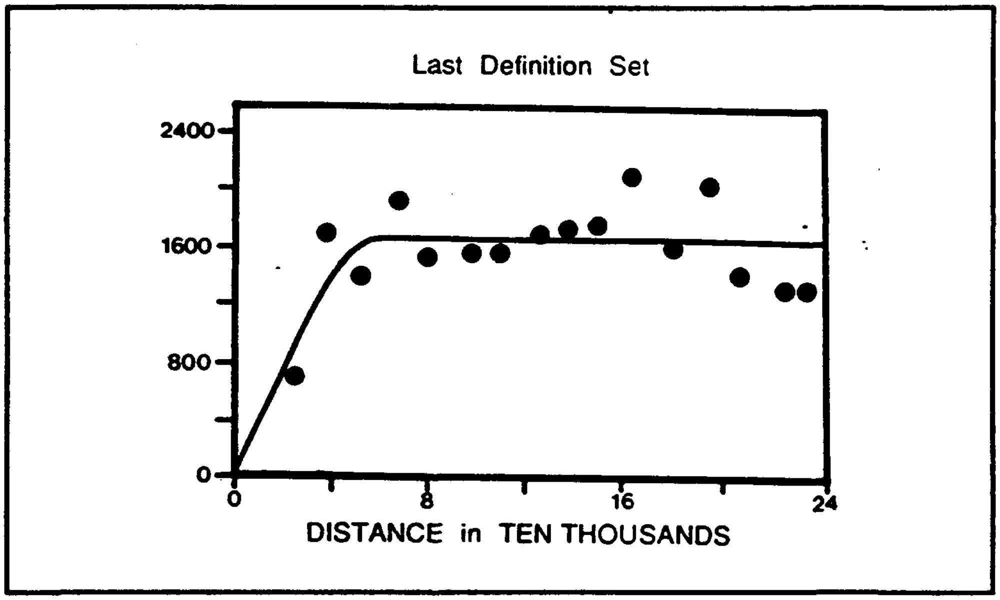
Brazos river rationale for exploration



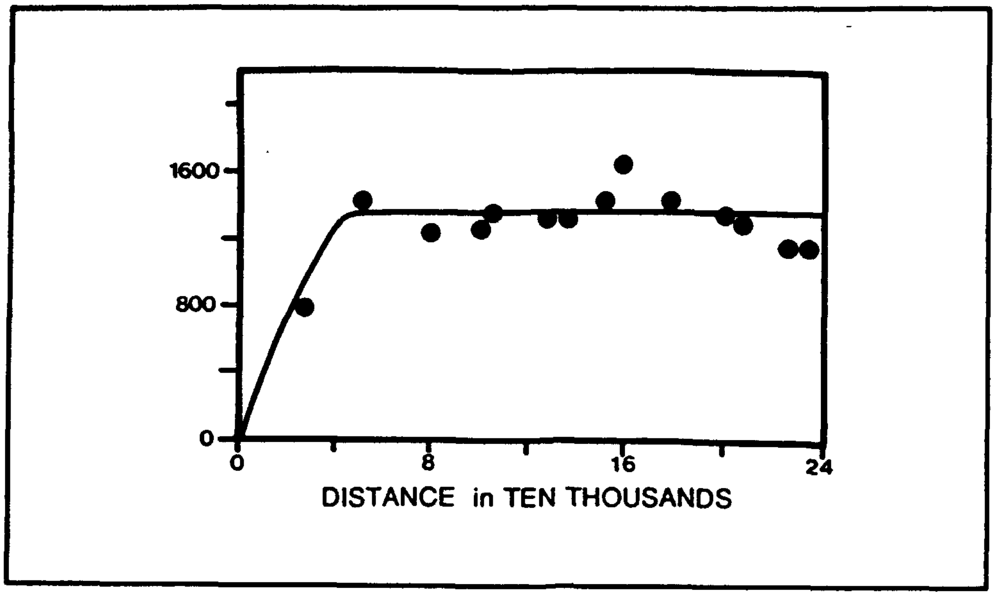


Brazos river rationale for exploration





Brazos river rationale for exploration



Brazos river grid method

Appendix G
Core Descriptions

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: J.May & B.Murphey Operator: F.Stewart Other: SP-8

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	6/4/80	0.0				0.0	1.5	Shovel		Sand, brown, silty (SM) dry, med.
2	6/4/80					5.0	6.5	Mudpit		Same as above, a little coarser.
				0.0	10.0			4" Rockbit		
3	6/4/80	10.5	10.5			10.5	11.5	Splitspoon	5/8/10	Sand, fine to coarse (SW) dry some grains to 1/8" dia., finer at top.
4	6/4/80	16.5	16.5			15.0	16.5		12/12/17	Sand, brown fineto coarse, (SW)
5	6/5/80					20.0	21.5		7/12/21	Sand, tan, med. to coarse, silty (SM-SW) gravelly.
6		25.5	25.5			25.0	26.0		26/51	Sand as above to 25.5 then brown med grained sand SM highly oxidized-strong chem. ordor.
7	6/5/80					30.0	31.5	Splitspoon	10/2/50	Sand, red brown, silty, med (SM).

Sheet 1 of 7 Sheets

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: J.May & B.Murphey Operator: F.Stewart Other: SP-8

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
8	6/5/80					35.0	35.5		50 for 5	Sand, as above (ordor)
9	6/5/80					40.0	41.5	V/D	4/17/15	Clay shale, weathered gray & (CH) brown.
10						45.0	45.5			Clay shale, as above change at 45.2 to fn grd light gray (SM).
11	6/5/80		54.8			50.0	50.4		60 for 4	Sand, tan med grd (SM).
12	6/5/80	54.8				55.0	56.5		10/27/37	Clay, br to tan, bentonitic (CH)
13	6/5/80					60.0	60.3		50 for .3'	Clay, black, lignitic friable, wet (OL).
14	6/5/80					65.0	65.4		60 for .4'	Sandstone, gray, weakly ind. (SM) moist.
15	6/5/80					69.0	69.5		50 for .5'	Siltstone, clayey, gray (MH).

Sheet 2 of 7 Sheets

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: Z.E.Bell Operator: F. Stewart Other: SP-8

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
16	7/16/80	72.0		72.0	74.0	73.0	73.5	Pitcher		Fine, moist, silty, oxidized sands with thin lenses ($\leq \frac{1}{2}$") of silty clay. Olive yellow 2.5Y6/8.
17	7/16/80			74.0	76.5	75.0	75.5	Pitcher		Wet sands as above with zones cemented by iron oxide. Olive yellow 2.5Y6/6.
18	7/16/80			76.5 78.9 81.4	78.9 81.4 83.9	77.0	77.5	Pitcher		Wet sands as above with thin lenses of claystone. (Fractured by sampler) light olive brown 2.5Y5/6.
19	7/16/80		87.0	83.9	86.5	85.5	86.0	Pitcher		Sand as above with thin claystone and siltstone lenses (lenses <10% of spl) and org. remains. Olive yellow 2.5Y6/8.
20	7/16/80	87.0		86.5	87.9	87.0	87.5	Pitcher		Sand in upper 6" of spl, siltstone grading to slickensided claystone at bottom of spl. Slickensided surfaces are oxidized. Strong brown/dk gray

Sheet 3 of 7 Sheets

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: Z.E.Bell Operator: F. Stewart Other: SP-8

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
21	7/16/80			87.9	90.1	88.0	88.5	Pitcher		Silty and sandy lenses in claystone grading to clays in lower part of drive. Grayish brown 2.5Y5/2 to lt. brownish gray 6/2.
22	7/16/80			90.1 92.5	92.5 94.3	91.5	92.0	Pitcher		Slickensided claystone w/org. remains. Dark grayish brown 2.5Y4/2.
23	7/16/80			94.3	96.8	95.0	95.5	Pitcher		Claystone as above with a 9" silty lense. Spl was saturated. Very dk gray. 2.5YN3 to N5.
24	7/16/80	98.2	98.2	96.8 98.9	98.9 101.3	98.0	98.5	Pitcher		Laminated siltstone with org. remains, spl. was saturated. Grayish brown 2.5Y5/2.
25	7/16/80			101.3 103.4 105.6	103.4 105.6 106.7	102.0	102.5	Pitcher		Siltstone, moist, with a blocky irregular fracture pattern. Lt brownish gray 2.5Y6/2.
26	7/16/80			106.7 109.2	109.2 110.7	107.0	107.5	Pitcher		Siltstone, moist, brittle with an irregular fracture pattern and org. remains. Light brownish gray 2.5Y6/2.

Sheet 4 of 7 Sheets

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: Z.E.Bell Operator: F. Stewart Other: SP-8

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
27	7/16/80			110.7	113.2	111.0	111.5	Pitcher		Siltstone, moist, brittle, dk gray 2.5YN4.
28	7/17/80			113.2 115.4	115.4 117.6	114.5	115.0	Pitcher		Claystone with org. remains, leaf imprints, laminated, very dk gray 2.5YN3.
29	7/17/80			117.6 119.5	119.5 120.8	118.0	118.5	Pitcher		Claystone as above with numerous silty laminations, saturated, light brownish gray 2.5Y6/2.
30	7/17/80		126.0	120.8 123.2	123.2 125.7	121.0	121.5	Pitcher		Claystone, moist with slickensides, dk gray brown 2.5Y4/2.
31	7/17/80	126.0	129.5	125.7 127.7	127.7 129.0	126.0	126.5	Pitcher		Lignitic clay with org. imprint friable, moist, very dk gray 10YR3/1.
32	7/17/80	129.5		129.0 129.6	129.6 132.0	130.0	130.5	Pitcher		Siltstone with thin, irregular laminations and fine sand lenses, and org. remains, light gray brown to black, 2.5Y5/2, spl. is saturated in sand lenses.

Sheet 5 of 7 Sheets

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: Z.E.Bell Operator: F.Stewart Other: SP-8

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
33	7/17/80			132.0	134.5	132.0	132.5	Pitcher		Siltstone with 2 8" silty fine sand lenses, org. remains.
				134.5	136.8					
				136.8	139.2					Spl. is laminated with numerous thin silt & sand zones, light brownish gray 2.5Y6/2. Sands and silts are saturated.
			140.5							
34	7/17/80	140.5		139.2	141.6	140.0	140.5	Pitcher		Siltstone as above grading to fine dark grayish brown sand 2.5Y4/2. Sands are saturated, fine grained.
35	7/17/80			141.6	144.2	143.0	143.5	Pitcher		Saturated, silty, fine sands with silty lenses (≤¼") containing org. remains. Grayish brown 2.5Y5/2.
36	7/17/80			144.2	146.6	145.0	145.5	Pitcher		Saturated fine sands with fewer and thinner silty lenses than above spl, gray 2.5Y5/1.
			146.0							

Sheet 6 of 7 Sheets

Boring No. 1123 Project: RMA South Plants (WES) Date: 06/05 Location: 02
Drill Rig: Failing 1500 Inspector: Z.E.Bell Operator: F.Stewart Other: SP-8

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
37	7/17/80	146.0		146.6 148.9 149.6	148.9 149.6 151.3	147.0	147.5	Pitcher		Lignitic clay with org. imprints, thinly bedded, fracture pattern approx. horizontal, moist, black 2.5YN2.
			153							
38	7/17/80	153.0		151.3	153.9	153.0	153.5	Pitcher		Moist, claystone, irregular fracture pattern, contains org. remains, dark gray 2.5YN4.
										[See Diagram for Piezometer Data]

Sheet 7 of 7 Sheets

Boring No. 1124 Project: RMA Date: 6/4/80 Location: 02

Drill Rig: Failing 1500 Inspector: Murphey Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
1	6/4/80	0.0		0.0	1.5	0.0	1.5	Surface		Brown silty sand dry med
										grained w/roots
				1.5	5.0					
2				5.0	6.5	5.0	6.5	from mud		Same, moist, no roots, med
								pit		grained
				6.5	10.0			5"fishtail		
3				10.0	10.5	10.0	11.5	standard	5	Same (brownish) -?- gravelly
								s.s.		coarse
				10.5	11.0				7	moist
				11.0	11.5				8	
				11.5	15.0			5" fishtail		
4			16.0	15.0	15.5	15.0	16.5		9	med to -?- (sm) 16.0-16.5
		16.0		15.5	16.0				10	clayey silt, fine sand sc-sm
				16.0	16.5				9	moist -?- cohesive
				16.5	20.0			5"fishtail		
5				20.0	20.5			Stnd s.s.	6	Same (sc-sm,fine to med.sand)
										some cohesion
				20.5	21.0				9	occ. 1/8" to 1/2" white wthrd
										calcarous
				21.0	21.5				14	nodules
				21.5	25.0			5"fishtail		
6				25.0	25.5			s.s.	5	Same, damp
				25.5	26.0				8	
				26.0	26.5				10	
				26.5	30.0			5"fishtail		
7				30.0	30.5			stnd.s.s.	8	Same, sc-sm,occ. med to coarse

Sheet 1 of 10 Sheets

Boring No. 1124 Project: RMA Date: 6/4/80 Location: 02
Drill Rig: Failing 1500 Inspector: Murphey Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
				30.5	31.0				8	mostly fine sand-damp
				31.0	31.5				7	
			33.0	31.5	35.0			5"Fishtail		
8		33.0		35.0	35.5	35.0	36.5	s.s.	11	Saturated fine silty sand sm/ loose
				35.5	36.0				11	
				36.0	36.5				9	
				36.5	40.0			5"fishtail		
9				40.0	40.5	40.0	41.5	stnd. s.s	6	Very moist fine silty sand sm loose
				40.5	41.0				5	
				41.0	41.5				8	
			44.0	41.5	45.0			5"fishtail		
10		44.0		45.0	45.5	45.0	46.0	Stnd.s.s.	19	Med. to cs sorted sand(sp) saturated
				45.5	46.0				23	
				46.0	46.5				11	
			48.0	46.5	50.0			fishtail		
11		48.0		50.0	50.5	50.0	51.5	stnd.s.s	4	silty clayey fine sand (sc-sm) cohesive
				50.5	51.0				7	some med. sand moist as above
				51.0	51.5				8	at 16.0-33.0.Occ.white cal-careous nodules
				51.5	55.0			fishtail		
12				55.0	55.5	55.0	56.5	stnd.s.s	7	clayey sand(sc),cohesive,more
				55.5	56.0				9	clay than above, damp
				56.0	56.5				14	

Sheet 2 of 10 Sheets

Boring No. 1124 Project: RMA Date: 6/4/80 Location: 02
Drill Rig: Failing 1500 Inspector: Murphey Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
				56.5	60.0			Fishtail		
13			60.2	60.0	60.5	60.0	61.5	Stnd.s.s.	18	60.0-60.2 sc as above
		60.2		60.5	61.0				27	60.2-61.5 saturated med. to coarse
				61.0	61.5				26	sand sp as above at 44.0-48.0
			64.0	61.5	65.0			fishtail		
		64.0								clay (cl) brown
14			65.0	65.0	65.5	65.0	66.5	stnd.s.s	27	med to coarse sp sand,moist
		65.0		65.5	66.0				28	a little clay(cl)at top,thickness unknown
				66.0	66.5				37	estimate sand is very moist to saturated
				66.5	70.0			fishtail		
15				70.0	70.5			stnd.s.s	24	coarse sp saturated sorted sand
				70.5	71.0				31	(tan,arkosic as above) coarse than #14
				71.0	71.5					
				71.5	75.0			fishtail		
16				75.0	75.5			stnd.s.s		coarse sp saturated sand as above
				75.5	76.0					
				76.0	76.5					
				76.5	80.0			fishtail		
17	6/5/80			80.0	80.5			stnd. s.s.	21	Same,saturated coarse sp
				80.5	81.0				22	
				81.0	81.5				24	

Sheet 3 of 10 Sheets

Boring No. 1124 Project: RMA Date: 6/4/80 Location: 02

Drill Rig: Failing 1500 Inspector: Murphey Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
			82.0	81.5	85.0			fishtail		
18	6/5/80	82.0	85.3	85.0	85.5				16	86.0 to 86.3 GW pebble gravel
		85.3	86.0	85.5	86.0				19	(igneous pebbles rounded to
		86.0		86.0	86.5				23	subangular, saturated up to
				86.5	90.0			fishtail		5/8" pebbles recov. 85.3
			89.0							-86.0 is sp -?- saturated
										86.0-86.5 is "dirty" black-
										brown silty fine sand sm,
										saturated
19		89.0		90.0	90.5	90.0	91.5		12	Only 0.6"-?- Probably compres-
				90.5	91.0				18	sed in spoon.Clayey cohesive
				91.0	91.5				14	fine to coarse silty,gravelly
										less clayey in bot. of drive
				91.5	95.0			rockbit		
20	6/5/80			95.0	95.5	95.0	96.5	stnd.s.s	8	Clayey silt "dirty"(black-br)
				95.5	96.0				8	fine to med cohesive sand.
										moist but tight.
				96.0	96.5				9	Clay content probably ≳5%
										this stratum resembles old
										soil profile
			99.0	96.5	100.0			rockbit		
21		99.0		100.0	100.5	100.0	101.0	stnd.s.s	27	Bedrock-black organic peat or
				100.5	101.0				51	lowgrade lignite,100%.Not
										strong,crumbles in hand
				101.0	101.3				47	Slightly hard at top of sample
										w/some clay laminae at top,wet

Sheet 4 of 10 Sheets

Boring No. 1124 Project: RMA Date: 6/4/80 Location: 02
Drill Rig: Failing 1500 Inspector: Murphey Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
				101.3	104.0			Rockbit		
				104.0	104.6			Stnd. s.s	77	Same
				104.5	104.6					
				104.6	110.0			Rockbit		
			110.3	110.0	110.5				129	110.0-110.3 bro-blk peat to
		110.3								lignite. 110.3-110.5 Gray fine
										silty sand sm wet
				110.5	114.1			Rockbit		Driller reports hard, stickey
				114.1	114.5				95	Silt (ML) gray, finer gradation
										of SM above, wet
				114.5	120.0					
25				120.0	120.5	120.0	120.5	s.s	88	Gray silt, same cohesive,but
										still wet (ml)
				120.0	125.0			Rockbit		
26				125.0	125.5	125.0	125.7	s.s	51	Gray silt as above, some co-
										hesive
				125.5	125.7				25	fairly tight,harder to scratch
										than above
			128.0							thinly laminated
				125.7	130.0			Rockbit		drilled easy
27	6/5/80	128.0		130.0	130.5	130.0	130.2	Stnd.s.s		Saturated gray (salt & pepper)
										med. grained sand (SP)
			131.2	130.4	131.2	hard		Rockbit		
28		131.2	132.5	131.2	131.7	131.2		s.s	29	Hallelajah! Blue gray clayshale
				131.7	132.2		132.2		70	tight cohesive(sticks together

Sheet 5 of 10 Sheets

Boring No. 1124 Project: RMA Date: 6/4/80 Location: 02
Drill Rig: Failing 1500 Inspector: Murphey Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
										-?- poor)

Set casing at 132.5

Summary Note: Bedrock at 99.0' 99.0-110.3 low grade lignite
upper zone {110.3 - 128.0 wet silt (ML) to silty sand (sm) gray
{128.0 - 131.2 saturated sand SP
131.2 - 132.5 Blue gray clayshale

(Casing actually at 99.5)

Sheet 6 of 10 Sheets

Boring No. 1124 Project: RMA SP- Denver Formation Date: 7/15/80 Location: Sec 02
Drill Rig: Failing 1500 Inspector: Zebell Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
29	7/15/80			132.6	134.0	132.6	133.0	Pitcher		Moist, cemented fine sands with silts, hard, irregular fracture pattern, dk gray 2.5YN4. Spl has some small oxidized zones
30		133.0	133.0			133.5	134.0			Claystone, slickensided, with org remains, moist, dk grayish brown 2.5y4/2
31				134.0	136.4	135.0	135.5			Claystone, mottled, with silty zones & org remains moist dk gray 2.5YN4 to gray N6
32				136.4	138.5	137.5	138.0			Friable claystone, soft, with org. remains and irregular fracture pattern. Drive had a 6" fine sand lense. V. dk grayish brown 2.5y3/2
33				138.5	140.5	139.0	139.5			Claystone as above
				140.5	143.0					
34				143.0	145.0	144.0	144.5			Claystone as above
35	7/16			145.0	147.2	146.0	146.5			Claystone as above
36				147.2	149.5	148.0	148.5			Claystone with thin silty lenses, saturated and thin sandy lenses (fine) at bottom of spl, light brownish gray
				149.5	151.8					

Sheet 7 of 10 Sheets

Boring No. 1124 **Project:** RMA SP-Denver Formation **Date:** 7/15/80 **Location:** Sec. 02
Drill Rig: Failing 1500 **Inspector:** Zebell **Operator:** Taylor **Other:** SP-13

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
										2.5y6/2 to dk grayish brown 2.5y4/2
37				151.8	153.6	152.5	153.0			Claystone as above
			156.8	153.6	155.9					
38		156.8		155.9	158.2	156.5	157.0			Claystone grades to lignite at 156.8 moist, friable, black 2.5yN2
			159.5	158.2	160.5					
39		159.5		160.5	162.5	161.0	161.5			Lignite above grades into thin alternating lenses of silts sands and clays, light gray 2.5yN6 to v.dk grayish brown 2.5y3/2
40			162.5	162.5	165.0	162.5	163.0			Abrupt chg to lignite at 162.5 lignite has smell oxidized zones and is interbedded with clays w/org remains crumbles into thin plates easily, moist, black 2.5yN2
		162.5								
41				165.0	167.1	165.0	165.5			Lignitic clays as above
				167.1	169.5					
42			172.0	169.5	171.9	169.5	172.4			Lignitic clays as above
43		172.0	171.9	171.9	174.2	171.9	172.4			clays, silts and sands in spl clayballs and org remains are in lenses to 1 1/2" in thickness. Moist, irregular fracture pattern.Olive brown to light gray 2.5y4/4-7/2

Sheet 8 **of** 10 **Sheets**

Boring No. 1124 Project: RMA SP-Denver Formation Date: 7/15/80 Location: Sec. 02
Drill Rig: Failing 1500 Inspector: Zebell Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
44	7/17/80			174.2	176.0	175.0	175.5			Interbedded clays and silts with some org remains, lenses from 1/2" - 1 1/2" moist, light brownish gray 2.5y6/2 to dk grayish brown 2.5y4/2
45			178.0	176.0	177.9	176.5	177.0			Claystone with org/lignitic seams, moist, black 2.5yN2
46		178.0		177.9	180.0	178.0	178.5			Claystone grading to siltstone with organics. Siltstone grades to fine silty sands at 179.0' lt. grayish brown 2.5y6/2
47				180.0 182.3	182.3 184.7	181.0	181.5			Silty fine grained sands, no bedding uniform in appearance, dark gray 2.5yN4, saturated
48				184.7	187.3	186.0	186.5			Sand as above with thin silty lenses (≤ 1/2")
49				187.3	189.6	---	---			Received only a small hard sandstone fragment cemented with pyrite. spl had org remains
50			193.7	189.6	192.0	191.0	191.5			Silty sandstone with org. remains and clay lenses dk grayish brown 2.5y3/2

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Boring No. 1124 Project: RMA SP-Denver Formation Date: 7/15/80 Location: Sec. 02

Drill Rig: Failing 1500 Inspector: Zebell Operator: Taylor Other: SP-13

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
51		193.7		192.0	194.4	193.5	194.0			Abrupt contact between cemented silty sands and claystone. Olive yellow 5y6/6 light olive gray 5y6/2

Sheet 10 of 10 Sheets

Boring No. 1143 Project: Rocky Mountain Arsenal Date: 11/8/80 Location: 01

Drill Rig: Mobile Inspector: R.W.Hunt Operator: Harried Other: SP-16

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	11/8/80	0.0	2.0	0.0	1.5	0.0	1.5	Standard Splitspoon	4-10-13	Sm, silty sand loose to compacted, dry, dark yellowish brown 10YR4/6.
2	11/8/80	2.0		4.0	5.5	4.0	5.5		12-22-20	Sp sand slightly compacted, dry, fine grained, brownish yellow 10YR6/6.
3	11/8/80			9.0	10.5	9.0	10.5		5-6-6	Sp sand slightly cohesive, very fine grained, moist-wet, yellowish brown, 10YR5/6.
4	11/8/80			14.0	15.5	14.0	15.5		8-12-15	Sp sand slightly cohesive, fine grained, saturated, yellowish brown, 10YR5/6.
5	11/8/80	20.0	20.0	19.0	20.5	19.0	20.5		5-8-13	Sp as above but med. grained. CH, fat clay, firm-stiff, moist yellowish brown. 10YR5/4.
6	11/8/80		27.0	24.0	25.5	24.0	25.5		11-12-19	CH, (as above) with occ. thin lenses of fine-med. grained sand.
7	11/8/80	27.0		29.0	30.5	29.0	30.5			SC, clayey sand, med. grained, soft-firm, wet, yellowish br. 10YR5/4.

Sheet 1 of 6 Sheets

Boring No. 1143 Project: Rocky Mountain Arsenal Date: 11/8/80 Location: 01
Drill Rig: Mobile Inspector: R.W. Hunt Operator: Harried Other: SP-16

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
8	11/8/80	35.0	35.0	34.0	35.5	34.0	35.5		15-25-38	SM-SC (in upper 1.0') silty sand, sat. soft, yellowish brown, 10YR5/4 SP, non-cohesive, med. grained sand, saturated, yellowish brown 10YR5/4
9	11/8/80			40.0	41.5	40.0	41.5		6-12-22	SP (sand as above) (Pale brown
10	11/8/80			44.0	45.5	44.0	45.5		6-13-33	10YR6/3 (NOTE) sand is coming up in hollow stem auger and having to be washed out before sample can be taken from bottom.
11	11/8/80			49.0	50.5	-	-	No Recovery	-	Tried several time to obtain a sample without success-sand still coming up in auger.
12	11/8/80			54.0	55.5	55.0	55.5	Split Spoon		SP (as above) sand w/some pea gravel Sand still coming up in auger.

Sheet 2 of 6 Sheets

Boring No. 1143 Project: Rocky Mountain Arsenal Date: 11/8/80 Location: 01

Drill Rig: Mobile Inspector: R.W. Hunt Operator: Harried Other: SP-16

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
13	11/11/80			59.0	59.5	59.0	59.5		122/0.5'	GC, clayey, sandy gravel (pea size gravel) saturated pale brwon (10YR6/3)
14	11/12/80	64.0		64.0	64.5	64.0	64.5		100/0.5'	Clayshale hard, moist, dark gray, 5Y4/1
15	11/19/80			69.2	72.2	71.7	72.2	Pitcher		Clay shale, stiff, massive to micro-laminated with silt, slightly fissile and fractured in places, sporadic organic fragments and slickensides. Predominantly very dark gray (5Y3/1), but black (5Y2.5/1) where lignitic;lignitic black (5Y2.5/1)
16				72.2	74.6	74.1	74.6			
17				74.6	76.8	76.3	76.8			
18				76.8	78.7	78.2	78.7			
19				78.7	81.2	80.7	81.2			
20				81.2	83.7	83.2	83.7			
21				86.2	86.2	85.7	86.2			
22				88.2	88.2	87.7	88.2			
23	11/19/80			88.2	90.7	90.2	90.7	Pitcher		Clayshale as above
24			91.5	90.7	93.2	92.7	93.2			
25		91.5		93.2	95.7	95.2	95.7			Fine sandy siltstone, tight, clean,very dark gray (5Y3/1)
26			97.2	95.7	98.2	97.7	98.2			
27	11/20/80	97.2	98.5	98.2	99.7	99.2	99.7			Clay shale, stiff, very dk gray (5Y3/1).
28		98.5	99.8	99.7	102.2	101.7	102.2			Sandstone, tight, fine,streak of clay shale, very dk gray (5Y3/1)

Sheet 3 of 6 Sheets

Boring No. 1143 Project: Rocky Mountain Arsenal Date: 11/8/80 Location: 01
Drill Rig: Failing 1500 Inspector: L.M. Smith Operator: Stewart Other: SP-16

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
28	11/20/	99.8								Clayey siltstone, tight, with
										clay shale laminae
			101.5							(sand lense 101.0-101.2) very
										dary gray (5Y3/1)
29		101.5		102.2	104.2	103.7	104.2			Clay shale, stiff, slightly
										organic in streaks
30				104.2	106.7	106.2	106.7			small slickensides, very dark
										gray (5Y3/1)
31			108.2	106.7	109.2	108.7	109.2			
		108.2		109.2	111.7	109.2	111.7	Undisturbed		Sandstone, tight, fine, sporadic
										clay shale
32				111.7	113.2	112.7	113.2			lenses, fines upward, wet, med.
										grained at
33			115.2	113.2	116.7	116.2	116.7			bottom, dark gray (5Y4/1)
34		115.2		116.7	119.2	118.7	119.2			Clay shale, stiff, organic frag-
										ments, slickensides,
35			121.0	119.2	121.7	121.2	121.7			fractured in places, becoming
										lignitic
36		121.0	123.7	121.7	124.2	123.7	124.2	Pitcher		Lignite, hard, brittle, frac-
										tured, black (5Y2.5/1)
37		123.7		124.2	126.7	126.2	126.7			Clay shale, stiff, organic
										fragments, slightly
38			127.9	126.7	129.2	128.7	129.2			brittle, very dark gray (5Y3/1)
39		127.9	129.5	129.2	130.7	130.2	130.7			Sandstone, silty, fine, tight,
										some organic fragments, micro-
										laminae of clayshale, dk gray

Sheet 4 of 6 Sheets

Boring No. 1143 Project: Rocky Mountain Arsenal Date: 11/20/80 Location: 01
Drill Rig: Failing 1500 Inspector: L.M. Smith Operator: Stewart Other: SP-16

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
39	11/20	127.9	129.5	129.2	130.7	130.2	130.7			(continued) (5Y3/1)
40		129.5		130.7	133.2	132.7	133.2			Clay shale, stiff, slickensides fractured
41				133.2	135.7	135.2	135.7			in places, sporadic organic fragments
42				135.7	138.2	137.7	138.2			very dark gray (5Y3/1) to black
43				138.2	140.7	140.2	140.7			(5Y2.5/1) where lignitic, brittle
44				140.7	143.2	142.7	143.2			where lignitic
45			145.7	143.2	145.7	145.2	145.7			very lignitic
46		145.7		145.7	148.2	147.7	148.2			Coal and lignite, hard, brittle fractured
47				148.2	150.7	150.2	150.7			black 5Y2.5/1
			151.7							
48		151.7		150.7	153.2	152.7	153.2			Clay shale, stiff, organic to 152.8, fractured
49			155.7	153.2	155.7	155.2	155.7			153.0-154.7, very dark gray (5Y3/1)
50	11/21	155.7	156.5	155.7	158.2	157.7	158.2	Pitcher		Sandstone, silty, tight, very dark gray (5Y3/1)
		156.5	157.9							clay shale, stiff, slickensides very dark gray (5Y3/1)
		157.9		158.2	160.7	158.2	160.7	Undisturbed		Sandstone, fine to med. clean wet

Sheet 5 of 6 Sheets

Boring No. 1143 Project: Rocky Mountain Arsenal Date: 11/20/80 Location: 01
Drill Rig: Failing 1500 Inspector: L.M. Smith Operator: Stewart Other: SP-16

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
51	11/21		163.9	160.7	163.2	162.7	163.2			very dark gray (5Y3/1)
52		163.9		163.2	165.7	165.2	165.7			Clay shale, silty, stiff, very dark gray
53			167.7	165.7	167.7	167.2	167.7			(5Y3/1)

Sheet 6 of 6 Sheets

Alluvial Boring Sec. 02022

Boring No. 1148 **Project:** RMA **Date:** 11/24/80 **Location:**

Drill Rig: Mobile B-53 **Inspector:** R.Hunt **Operator:** B.Harried **Other:** SP-12

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	11/24/80	0.0 2.5		0.0	1.5	0.0	1.5	splitspoon (std)	21-27-27	SM,silty sand,firm,mod. cohesive,moist brown-dk brown, 10yr4/3
2		2.5		4.0	5.5	4.0	5.5		11-18-17	SP,fine-med.grained sand, non-cohesive,moist, yellowish brown,10yr5/6
3				9.0	10.5	9.0	10.5		5-5-6	SP (as above) saturated
4				14.0	15.5	14.0	15.5		3-3-2	SP (as above) with silt saturated
5			23.0	19.0	20.5	19.0	20.5		18-40-26	SP fine-med grained sand (as above-without silt)
6		23.0	27.0	24.0	25.5	24.0	25.5		10-11-28	SM-SC,silty-clayey fine sand soft, saturated, yellowish brown, 10yr5/6
7		27.0	32.0	29.0	30.5	29.0	30.5		9-15-27	SW, fine-coars sand, non-cohesive, saturated yellowish brown 10yr5/6
8		32.0		34.0	35.5	34.0	35.5		13-28-31	SP,very fine-fine grained sand, non-cohesive,saturated yellowish brown, 10yr5/4
9			39.5	39.0	40.5	39.0	40.5		20-21-94	(0.3' med. coarse sand on top of Denver)
		39.5						-(top of Denver)-		clayshale,hard,oxidized, olive, 5y5/3 waxey
10			45.9	44.0	44.5	44.0	44.5		103/.5	

Sheet 1 of 4 Sheets

Alluvial Boring Sec. 02022

Boring No. 1148 **Project:** RMA **Date:** 11/24/80 **Location:**

Drill Rig: Mobile B-53 **Inspector:** R.Hunt **Operator:** B.Harried **Other:** SP-12

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
11	12/1/80			44.5	46.0	45.8	46.3	Pitcher		Recovered only 0.2'-took rest of spl from top of spl 12
12		45.9		46.0	48.5	48.0	48.5			<u>Sandstone</u>,<u>clayey</u>,with occ. clay lenses,soft-hard,
13				48.5	50.8	50.3	50.8			oxidized, wet, yellowish brown, 10yr6.8 fine & med.
14		52.0	52.0	50.8	53.1	52.6	53.1			grained,thinly bedded. <u>Sandstone</u>, hard-very hard,
15				53.1	55.4	54.9	55.4			find-coarse grained,thinly bedded, wet, very dark gray
16				55.4	56.2	55.7	56.2			5y3/1 with alternating yellowish brown oxidized
			56.2	56.2	57.3			-(Rock bit)		zones (as above) occ. clay lenses.
17				57.3	59.5	59.0	59.5			(Ran Rock bit from 56.2 to 57.3-very hard sandstone)
18	12/1/80	56.2		59.5	61.5	61.0	61.5			<u>Sandstone</u>,clayey, with occ. clayshale layers upto 0.8' thick and thin
				61.5	64.0			(Rock bit)		lenses hard fine-coarse grained wet, very dark gray 5y3/1 (60.5-61.3) clayshale, sdy,hard as well as
19				64.0	66.0	65.5	66.0			(66.7-67.3) fissile,organic black 5y2.5/1

Sheet 2 of 4 Sheets

Alluvial Boring Sec. 02022

Boring No. 1148 **Project:** RMA **Date:** 11/24/80 **Location:**

Drill Rig: Mobile B-53 **Inspector:** R.Hunt **Operator:** B.Harried . **Other:**

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
20				66.0	68.0	67.5	68.0			(65.0-66.0)-clayshale,hard, crumbly,with small secondary white
21				68.0	70.2	69.7	70.2			calcite crystals and mica, moist black 5y2.5/1
22				70.2	72.5	72.0	72.5			lignitic seams and streaks
			73.6							in bot. 2 ft
23	12/2/80	73.6		72.5	74.7	74.2	74.7			lignite, black(brownish)
			74.2							10yr2/1 (high grade)
		74.2								lignitic silty fine sand,
			74.7							compacted, wet,gray 5y5/1
24		74.7		74.7	76.7	76.2	76.7			Sand,fine grained,compacted wet, with occ. organic streak
25				76.7	78.7	76.7	78.7-	(left in tube)		med. grained toward bottom
26				78.7	81.0	80.5	81.0			
27			84.9	81.0	83.3	82.8	83.3			
28		84.9		83.3	85.6	85.1	85.6			varies between coal and
29				85.6	86.6	86.1	86.6			high grade lignite wet
30			88.8	86.6	88.7	88.2	88.7			black, 10yr2/1
31		88.8		88.7	90.9	90.4	90.9			Clayshale,hard blocky with occ. organic inclusions
			89.6							gray, 5y5/1 moist
		89.6								Sandstone, silty, very fine
			90.9							grained, hard,wet, gray 5y5/1

Sheet 3 of 4 Sheets

Alluvial Boring Sec. 02022

Boring No. 1148 **Project:** RMA **Date:** 11/24/80 **Location:**

Drill Rig: Mobile B-53 **Inspector:** R.Hunt **Operator:** B.Harried **Other:**

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
32		90.9		90.9	93.0	92.5	93.0			Clayshale (as above) dk gray
			91.8							5y4/1
		91.8								Sandstone silty, very fine
33			94.3	93.0	95.2	94.7	95.2			(as above)
34		94.2		95.2	97.3	96.8	97.3			compacted sand to soft
35				97.3	99.5	99.0	99.5			Sandstone, fine grained
36			102.4	99.5	102.1	99.5	102.5	(left spl in tube)		thinly bedded, wet gray 5y5/1
37		102.4		102.1	104.3	103.8	104.3			clayshale, hard, block, crumbly
										moist, dk greenish gray
			104.3							(no color code)
										104.3 - bot. of hole

Sheet 4 of 4 Sheets

Boring No. 1153 Project: RMA Date: 12/11/80 Location: 02
Drill Rig: Mobile B-53 Inspector: R.Hunt Operator: L.Flowers Other: SP-9

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	12/11/80	0.0	2.5	0.0	1.5	0.0	1.5	splitspoon std.	14-26-26	sm, silty sand, slightly to non-cohesive, dry, yellowish brown, 10yr5/6
2		2.5		4.0	5.5	4.0	5.5		8-6-6	sp, very fine-fine grained slightly silty, moist, slightly to non-cohesive
3			12.0	9.0	10.5	9.0	10.5		1-1-2	SP (similar to above) no silt, non-cohesive y-brn
4		12.0		14.0	15.5	14.0	15.5		5-9-16	SC, clayey sand, firm, fine, moist, yellowish brown, 10yr5/4
5			22.0	19.0	20.5	19.0	20.5		4-18-14	SC, (as above) small amount of caliche, very moist, (water on spoon)
6		22.0	27.5	24.0	25.5	24.0	25.5		15-33-43	SW, clayey, fine to coarse sand, saturated, dk yel br. 10yr4/4
7		27.5		29.0	30.5	29.0	30.5	(Denver contact 27.5')	12-26-38	Clayshale, firm, soapy, with oxidized streaks, moist, with olive 5y5/3
8				32.5	34.0	32.5	34.0		9-24-60	(as above) (34.0' bot of alluv spls).

Sheet 1 of 1 Sheets

Boring No. 1153 Project: RMA Regional Study Date: 2/13/81 Location: Sec. 02
Drill Rig: Failing 1500 Inspector: LTC.Zebell Operator: Taylor Other: SP-9

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	2/13/81			33.0	35.2	34.7	35.2	Pitcher		Claystone shale,oxidized/ weathered,moist, moderately plastic, olive yellow 2.5y6/6, uniform
2				35.2	37.4	36.5	37.0			Claystone shale, strongly oxidized in zones, spl with scattered veg. remains olive yellow to yellow 2.5y6/6-10yr7/8
3				37.4	39.5	39.0	39.5			(as above)
4				39.5	41.7	41.2	41.7			Claystone,shale has thin ≤1/4") silty sand lenses strongly oxidized in the lenses v. pale brown to yellow 10yr8/4-7/8, moist
5				41.7	44.0	43.2	43.7			
6			45.2	44.0	46.2	45.0	46.5			Sand, fine, wet, silty oxidized, crumbles easily olive yellow 2.5y6/6
7				46.2	48.2	47.5	48.0			
8			50.3	48.2	50.2	49.3	49.8			
9		50.3		50.2	52.4	51.5	52.0			Grading out of sands at 50.3 and into siltstones/ claystones, wet, strongly oxidized, drive has a silty sand lense between

Sheet 1 of 4 Sheets

Boring No. 1153 Project: RMA Regional Study Date: 2/13/81 Location: Sec. 02
Drill Rig: Failing 1500 Inspector: LTC.Zebell Operator: Taylor Other: SP-9

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
										51.8 and 52.0
10		53.5	55.1	52.4	54.5	54.0	54.5			Lignite lense between 53.5 - 55.1 wet, black, uniform
11		55.1		54.5	56.7	56.1	56.6			Claystone shale, moist, uniform, soapy luster, firm gray 5y5/1
12				56.7	59.0	58.3	58.8			Strongly oxidized sand lenses between 58.0 & 59.0 fine, silty, wet sand claystone above & below lense is oxidized for approx. one foot
13				59.0	61.2	60.3	60.8			Claystone shale, moist, hard, uniform, very dark gray 5y3/1, soapy luster
14				61.2	63.4	62.0	62.5			
15				63.4	65.5	65.0	65.5			Becoming highly organic between 65-68.0 spl is wet
				65.5	68.0					no spl, when driven from tube, the spl was pulverized
16				68.0	70.0	69.0	69.5			
17				70.0	72.3	71.8	72.3			
18				72.3	74.5	73.5	74.0			

Sheet 2 of 4 Sheets

Boring No. 1153 Project: RMA Regional Study Date: 2/13/81 Location: Sec. 02
Drill Rig: Failing 1500 Inspector: LTC.Zebell Operator: Taylor Other: SP-9

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
19				74.5	76.5	75.7	76.2			Fractured at bedding planes from 74.5 to 77.3, spl saturated
			77.0							
20		77.0		76.5	78.7	77.5	78.0			Siltstone with thin clay lenses (≤ 1/4") organic remains, has salt & pepper appearance,white to dark gray 2.5y8/2-n/3, moist, firm
21			81.5	78.7	81.0	79.0	79.5			
22		81.5		81.0	83.2	82.5	83.0			Claystone shale, moist firm, organic slickensided soapy luster, very dark gray to black 7.5yn3/2/
			85.0							
23		85.0		83.2	85.5	84.8	85.3			Siltstone,moist, crumbles easily, dull luster, has veg. remains, dark grayish brown 10yr4/2
			86.5							
24		86.5		85.5	87.5	86.5	87.0			coal, black glossy luster moist, hard fractures at Bedding planes
			88.0							
25	2/14	88.0 89.0	89.0	87.5	89.5	89.2	89.5			Coal grading to claystone shale then silty fine sand. Sand is soft, wet gray 2.5y6/
26				89.5	91.5	91.0	91.5			

Sheet 3 of 4 Sheets

Boring No. 1153 Project: RMA Regional Study Date: 2/13/81 Location: Sec. 02
Drill Rig: Failing 1500 Inspector: LTC .Zebell Operator: Taylor Other: SP-9

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
27				91.5	93.5	93.0	93.5			
28				93.5	95.7	95.2	95.7			
29			96.0	95.7	97.2	95.7	96.2			Sharp, well defined contact between sand and coal at 96 ft core is massive, hard black
		96.0								
30			97.0	97.2	99.1	98.0	98.5			
31		99.0	100.0	99.1	102.0	101.2	101.7			Coal grades to claystone shale (1 ft) from100' on there is silty, fine, saturated sands, gray-7.5yn6/
		100.0								
32			103.0	102.0	104.2	102.0	102.5			
		103.0								
33				104.2	106.3	105.8	106.3			Claystone shale, moist hard with org remains dark gray 2.5yn4/
			106.0							
34		106.0		106.3	108.5	107.5	108.0			wet, silty fine sands firm partially cemented gray 2.5yn5/ at 108 ft. is claystone shale.
			108.0							
					BOH	109.0	ft.			Sands are wet in fractures which are roughly horizontal

Sheet 4 of 4 Sheets

Boring No. 1155 Project: RMA Regional Study Date: 1/14/81 Location: Sec. 01
Drill Rig: Mobile B53 Auger Inspector: Maj. Zebell Operator: Herried Other: Sp-15

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	1/14	0.0	1.0			0.0	1.5	Splitspoon	3/4/6	SC grading into an SM near bottom of spl,moist grading to saturated at 1.5ft,veg. remains/odor,sands are fine spl has a 3" lense of clay w/fine sands at 1.0ft, moderately plastic and calcareous,
		1.0	3.0	(water at 1.5 ft)						yellowish brown 10yr5/4
2		3.0	7.0			4.0	5.5		4/6/11	S.C. w/alternating layers of sm, sc-cl, sands are fine, cl is moderately plastic,w/ sand, dark yellowish brown 10yr4/4
3		7.0	13.0			9.0	10.5		2/3/12	SP-clean, fine sands, pale brown 10yr6/3
4	1/15	13.0	18.0			14.0	15.5		12/18/17	SC-CL with thin lenses of SM (2-3"), sands, are fine to med. SC-CL is slightly to moderately plastic, light yellowish brown 10yr6/4
5		18.0				19.0	21.5		7/18/28	SM-fine sand w/fines non-plastic,light yellowish brown 10yr6/4
		23.0								

Sheet 1 of 4 Sheets

Boring No. 1155 Project: RMA Regional Study Date: 1/14/81 Location: Sec.01
Drill Rig: Mobile B53 Auger Inspector: Maj.Zebell Operator: Herried Other: SP-15

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
6		23.0				24.0	25.5		6/14/17	SP-clean fine sands with occ. med. sands light yellowish brown 10yr6/4 (Driller says drilling very easy at approx 23 ft.)
7						29.0	30.5			SP as above with more med. grained sands towards bot. of spl, bot. of spl has a 2" lense of CL w/coarse sands, pale brown 10yr6/3
8						34.0	35.5		4/7/40	SP(w/scattered pea gravel) as above
9						39.0	40.5		17/51/69	SP as above w/pea gravel
10			47.0			44.0	45.5		43/50/58	SP as above w/thin(3") clay lense
11		47.0				49.0	50.5		25/53/-	SM-with scattered gravel to 3/4" in dia.& thin (< 1/2") lenses of SC-CL yellowish brown 10yr5/4
12		53.0				53.0	53.5	(BR)	130/-/-	Unweathered Denver fm claystone/shale,moist,hard, massive,gray 10yr5/1, uniform in color, & texture (6" casings set at 58')

Sheet 2 of 4 Sheets

Boring No. 1155 Project: RMA Date: 3/2/81 Location:01

Drill Rig: 1500 Inspector: R.Hunt Operator: D.Taylor Other: SP-15

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
13	3/2/81	59.7		59.7	61.0	60.0	61.0	Pitcher		Alternating thin lenses of
										clayshale and very fine
14				61.0	62.0	61.0	62.0			sandy silt, firm, wet
			61.8							gray 5y5/1-dk gray 5y4/1
15		61.8		62.0	64.2	63.7	64.2			Clayshale,massive very firm
										fairly numerous slickensides
										moist,wet,silty toward
			64.5							bottom, gray 5y5/1
16		64.5		64.2	66.7	66.2	66.7			silty sand,very fine grained
										thinly bedded compacted
										occ. thin lenses of clay
17				66.7	69.0	68.5	69.0			wet: fine sand content
										reduces to sandy silt in
18			71.5	69.0	71.0	70.3	71.0			bottom 2' gray 5y/51
19		71.5		71.0	73.2	72.7	73.2			Clayshale thinnly bedded w/
										occ. silt partings in top
										portion,massive in bot.half
20	3/10/81			73.2	75.5	75.0	75.5			w/slickensides,mod. hard
21				75.5	77.5	77.0	77.5			moist with lignitic horizons
22				77.5	79.7	79.2	79.7			very dk gray 5y3/1
23				79.7	81.7	81.2	81.7			to dk gray 5y4/1
24				81.7	83.7	83.4	83.7			
25				83.9	86.0	85.5	86.0			Occ.silt and sand lenses
26				86.0	88.0	87.5	88.0			and organic partings below
27				88.0	90.1	89.6	90.1			86.0'

Sheet 3 of 4 Sheets

Boring No. 1155 Project: RMA Date: 3/2/81 Location: 01
Drill Rig: 1500 Inspector: R.Hunt Operator: D.Taylor Other: SP-15

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
28			91.5	90.1	92.3	91.3	92.3			
29		91.5		92.3	94.4	92.4	94.4			Clayshale,sandy,massive
30				94.4	96.0	95.5	96.0			with occ. sand and silt
31				96.0	98.2	97.7	98.2			lenses,moist,moderately
32			97.2	98.2	100.0	99.5	100.0			hard,very dk gray 5y3/1
		97.2								silty sand,very fine-fine
33				100.0	102.2	100.0	102.2	-Left spl in tube-		grained with alternating
										clayshale lenses, moderately
34			103.7	102.2	104.3	103.8	104.3			hard,moist,dk-very dk gray
										5y4/1-3/1
35	3/10/81			104.3	106.5	106.0	106.5			alternating brown lignitic
										lenses & inclusions in bot.
										1 1/2'
		103.7								Clayshale massive,fairly
										blocky,crumbly,numerous
			106.5							slickensides, very dk gray
										5y3/1 moist, wet
										Bottom Depth - 106.5'

Sheet 4 of 4 Sheets

Boring No. 1160 Project: RMA Regional Study Date: 1/19/81 Location: 36

Drill Rig: Mobile B-53 Inspector: Maj. Zebeu Operator: Herried Other: SP-2

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	1/19/81	0.0	3.0			0.0	1.5	Split Spoon	17/24/22	SC-clayey, fine sand w/veg odor/remains, slight plasticity, lower half of SPL is calcareous moist, dark brown 10YR3/3 to brownish yellow 10YR6/6.
2		3.0	9.0			5.0	6.5		11/20/33	CL-Sandy (fine) clays, very calcareous, with a lense of sm with fine sands. Sm is loose Cl is firm, Cl has stringers and zones of calcite, moist, yellowish brown 10YR5/8 to white 10YR8/2
3		9.0				10.0	11.5		17/26/41	Denver FM weathered and calcified claystone shale, moist, SPL does not have calcareous zones or stringers in lower 3rd dark grayish brown to white 25Y4/2-N/8,firm
4						15.0	16.5		21/33/40	Strongly oxidized claystone shale, moderately plastic, moist firm, oxidation is concentrated in horizontal (bedding?) planes, SPL has some fine sands, light olive brown 2.5Y5/6 to dark brown 7/5YR 3/4

Sheet 1 of 5 Sheets

Boring No. 1160 Project: RMA Regional Study Date: 1/19/81 Location: 36
Drill Rig: Mobile B-53 Inspector: Maj. Zebeu Operator: Herried Other: SP-2

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
5			20.0 (±)			20.0	21.5		22/51/63	Moist, firm claystone shale slightly oxidized at top of SPL, no oxidation at bottom of SPL where color and texture are uniform, grayish brn 2.5Y5/2 (NOTE: This boring was left open overnight to see if water would seep into the hole - it did not, therefore, no piezometer was installed. Also, this hole rejected the auger at bottom drilling was very hard)

Sheet 2 of 5 Sheets

Boring No. 1160 Project: RMA Regional Study Date: 6/15/81 Location: 36
Drill Rig: FAiling 1500 Inspector: R.Hunt Operator: Black, Harried Other: SP-2

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
6	6/15/81	20.0 (±)		20.0	22.3	21.8	22.3	Pitcher		Volcaniclastic sediments, tough clay matrix containing numerous
7				22.3	24.3	23.8	24.3			sub-angular to angular rock and mineral
8				24.3	26.6	26.1	26.6			fragments that are generally ≤ 1/8" to coarse sand in
9				26.6	28.2	27.7	28.2			size but range upto 2±" in size. horizontal
10				28.2	30.7	30.2	30.7			bedding is indicated by occ thin clay partings
11				30.7	32.7	32.2	32.7			zone is weathered and oxidized, moist, color is olive yel. to
12				32.7	34.6	34.1	34.6			lt. olive brown, 2.5Y6/6 - 2.5Y5/4.
13				34.6	36.5	36.0	36.5			(35.4-36.4) claystone without rock fragments.
14			39.0	36.5	38.5	38.0	38.5			Bot. 2' is highly frac. & wet.
15		39.0		38.5	40.5	40.0	40.5			Clayey siltstone to very fine silty sandstone, thinly bedded,
16				40.5	42.6	42.1	42.6			zone is characterized by numer-ous tiny angular glass (obsid-ian)
17				42.6	44.6	44.1	44.6			fragments of grains which give a peppered effect, oxidized
18				44.6	46.5	46.0	46.5			along bedding in part. Lower 2' is highly fractured and

Sheet 3 of 5 Sheets

Boring No. 1160 Project: RMA Regional Study Date: 6/15/81 Location: 36
Drill Rig: Failing 1500 Inspector: R.Hunt Operator: Black, Harried Other: SP-2

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
19	6/15/81			46.5	48.5	48.0	48.5			oxidized and contains more clay, very moist-wet, color varies - lt olive gray 5Y 6/2, olive 5Y5/4 and olive
20			50.6	48.5	50.8	50.3	50.8			brown 2.5Y4/4.
21		50.6		50.8	52.9	52.4	52.9			Clayshale,hard,massive,waxey,
22				52.9	54.9	54.4	54.9			blocky,minor oxidation along some bedding & frac.,moist, num. organic
23			56.3	54.9	56.6	56.1	56.6			imprints, olive gray 5Y4/2
24		56.3		56.6	58.5	58.0	58.5			Attending, thinly bedded clay-shale & siltstone to very fine silty
25				58.5	60.0	59.5	60.0			Sandstone layers upto 1-1½' thick. Clayshale is hard w/ occ.
26				60.0	62.5	62.0	62.5			silt partings, silt & sand layers are weakly bonded to
27				62.5	64.7	64.2	64.7			compacted; numerous organic imprints, very moist-wet,
28			65.2	64.7	66.5	66.0	66.5			gray-dk gray 5Y5/1-4/1.
29		65.2		66.5	68.6	68.1	68.6			Clayshale,hard,massive,waxey,
30				68.6	70.7	70.2	70.7			blocky,moist,slickensides in
31	6/16/81			70.7	72.8	72.3	72.8			bot. half of zone-also becomes
32			76.3	72.8	74.8	74.3	74.8			crumbly, very dk gray 5Y3/1

Sheet 4 of 5 Sheets

Boring No. 1160 Project: RMA Regional Study Date: 6/15/81 Location: 36
Drill Rig: Failing 1500 Inspector: R.Hunt Operator: Black,Harried Other: SP-2

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
33		76.3		74.8	76.7	76.2	76.7			Lignite & highly organic clay shale, hard blocky, moist, very dk brown
34			77.8	76.7	78.6	78.1	78.6			10YR2/2.
35		77.8		78.6	80.6	80.1	80.6			Clayshale, hard,blocky,silty, w/silty partings & occ. organic imprints & inclusions, moist,dk
			83.7							to very dk gray, 5Y4/1-3/1
		83.7								Sand, very fine-fine, tightly compacted,clean, w/occ organic partings. Num. clayshale partings in top portion, wet,
			89.7							gray dk gray 5Y5/1-4/1
		89.7								Clayshale w/silt and very fine sand
			90.7							lenses (similar to above)
		90.7								Clayshale, hard,blocky-crumbly num. slickensides & organic inclusions, highly organic bot. 0.2-0.3', moist
			92.8							very dk gray, 5Y3/1 92.8-bot.

Sheet 5 of 5 Sheets

Boring No. 1185 Project: RMA Date: 3/11/81 Location: Sec. 35
Drill Rig: Mobile B53 Inspector: R.Hunt Operator: Harried Other: N-6

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	3/11/81	0.0	3.0	0.0	1.5	0.0	1.5	2"split-spoon	1-16-18	ML,sandy silt,fine grained soft moist, dk brown 10yr3/2
2		3.0	8.0	5.0	6.5	5.0	6.5		6-9-13	SM, fine grained silty sand soft-firm, caliche,moist brownish yellow 10yr6/6 -?-
3		8.0	13.0	10.0	11.5	10.0	11.5		4-6-10	ML,sandy silt,silty sand yellowish brown -?-
4		13.0		15.0	16.5	15.0	16.5		9-7-9	SC,Clayey fine sand with CL (? clay) firm, wet -?- yellowish br 10yr
5			22.0	20.0	21.5	20.0	21.5		4-7-17	(as above) only wet
6		22.0		25.0	26.5	25.0	26.5		2-5-?	CL, sandy clay with SC (-?- clayey sand) soft, wet, small -?- yellowish brown -?-
7				30.0	31.5	30.0	31.5		12-?	CL, sandy clay, fine gr.& firm, moist caliche yellowish brown -?-
8			37.5	35.0	36.5	35.0	36.0		10-19-21	GS gravel with ? sand small gravel
9		37.5		40.0	41.5	40.0	41.5		?-20-36	Clayshale firm with oxidized streaks pale olive -?-

Sheet 1 of 4 Sheets

Boring No. 1185 Project: RMA Date: 3/11/81 Location: Sec. 35

Drill Rig: Failing 1500 Inspector: R.Hunt Operator: Black Harried Other: N-6

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
10	6/19/81			42.5	44.1	43.6	44.1			Clayshale,hard,waxey,blocky crumbly, occ. to num. slickensides, highly oxidized along fractures & bedding (46.0+ to 48.5+) - hard clayshale in sub-angular chunks upto 1"+ size surrounded by soft clay from the parent source,clayshale chunks are bounded by slickensides,material does not appear to be cutting although it is similar. Also when hole was at the 58' depth & left to stand past lunch, it had caved in in this zone. Note: Later observation - zone above is most probably cuttings.
11				44.1	46.1	45.6	46.1			
12				46.1	48.3	47.8	48.3			
12a						47.3	47.8			
12b						46.8	47.3			
13				48.3	50.8	50.3	50.8			
14				50.8	53.3	52.8	53.3			
15				53.3	56.1	55.6	56.1			
16				56.1	58.6	58.1	58.6			
17			60.0	58.6	60.1	59.6	60.1			
18		60.0		60.1	62.0	61.5	62.0			Clayshale to clayey siltstone w/interbeds of clayey sand up to 0.5' thick, thinly bedded, blocky highly oxidized, moist, lt yellowish brown. 2.5y6/4-brownish yellow 10yr6/8.
19				62.0	63.5	63.0	63.5			
20	6/22/81		65.4	63.5	65.5	65.0	65.5			

Sheet 2 of 4 Sheets

Boring No. 1185 Project: RMA Date: 3/11/81 Location: Sec. 35
Drill Rig: Failing 1500 Inspector: R.Hunt Operator: Black Harried Other: N-6

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
		65.4								Coal and Lignite w/occ. Lense of pale brown micaeous soapy clay w/minor sand, blocky, hard,moist,black to very dk brown, 10yr2/1.2/2
21				65.5	66.5	66.0	66.5			
22				66.5	68.5	68.0	68.5			
23				68.5	70.6	70.1	70.6			
24			71.0	70.6	72.0	71.5	72.0			
		71.0								clayshale, silty, w/irregular silt & very fine sand partings hard, blocky,occ. organic inclusions, moist, dk gray 5y4/1-gray 5y5/1, waxey clayshale in bot. ft.
25				72.0	73.9	73.4	73.9			
26				73.9	75.9	75.4	77.9			
27				75.9	77.9	77.4	77.9			
28			79.6	77.9	79.9	79.4	79.9			
		79.6								sand, very fine-fine tightly compacted, thinly bedded,saturated, clean gray-5y5/1 occ. organic
29				79.9	81.9	81.4	81.9			
30			82.7	81.9	84.0	83.5	84.0			
		82.7								clayshale, w/fine silty sand inclusions, hard, blocky occ. organics, moist, dk greenish gray (no color code)
31				84.0	86.5	86.0	86.5			
32			87.0	86.5	88.5	88.0	88.5			
		87.0								clayshale, hard, bocky, num organic imprints, moist dk gray 5y4/1 becomes very dk gray (5y3/1) and crumbly w/num. slickensides below 88.7
33				88.5	90.5	90.0	90.5			
			90.4							

Sheet 3 of 4 Sheets

Boring No. 1185 **Project:** RMA **Date:** 3/11/81 **Location:** Sec. 35

Drill Rig: Failing 1500 **Inspector:** R.Hunt **Operator:** Black Harried **Other:** N-6

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
		90.4								Clayshale (same as between
34			92.5	90.5	92.6	92.1	92.6			(82.7 & 87.0)
35		92.5		92.6	94.6	94.1	94.6			Sandstone, very fine-fine
										In top to med. w/pea
										grav. size rounded clayshale
										balls in bot. 1 1/2'.mod.
36				94.6	96.6	96.1	96.6			hard, mod. to well bonded,
			96.7							wet, gray, 5y5/1
37		96.7		96.6	98.6	98.1	98.6			Clayshale, hard,blocky-crumbly
										num. slickensides, very moist
38				98.6	101.0	100.5	101.0			very dk greenish gray (no
			100.8							color code)
39		100.8		101.0	102.2	101.7	102.2			Clayey siltstone, hard,blocky
										occ. organic inclus., moist,
			102.8							dk gray 5y4/1
40	6/23/81	102.8		102.2	104.1	103.6	104.1			Clayshale,hard,blocky,massive
41				104.1	106.2	105.7	106.2			moist, dk gray-very dk gray
42				106.2	108.5	108.0	108.5			5y4/1-3/1 (104.0-106.0)
43			110.5	108.5	110.2	109.7	110.2			num. organics-crumbly
44		110.5		110.2	112.2	111.7	112.2			Silty clayshale, very tough,
45				112.2	114.2	113.7	114.2			hard, massive,blocky,moist
46			116.5	114.2	116.5	116.0	116.5			gray-dk gray 5y5/1-4/1
										Bot. depth - 116.5

Sheet 4 of 4 Sheets

Boring No. 1188 Project: RMA Date: 5/22/81 Location: 36

Drill Rig: Mobile Inspector: R.Hunt Operator: B.Harried/D.Taylor Other: E-1

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	5/22/81	0.0	1.0	0.0	1.5	0.0	1.5	2"Standard Splitspoon	3/8/14	ML, sandsilt, soft, moist, dk yel.br. 10YR3/4
		1.0	3.0							CL-ML, silty, sddy clay, micaeous, hard, moist (slightly) dk.yel.br.10YR4/4
2		3.0	8.0	5.0	6.5	5.0	6.5		9/11/12	ML, sandy silt, firm, dry, minor caliche,lt.yel. br. 10YR6/4
3		8.0	13.5	10.0	11.5	10.0	11.5		24/35/33	CL-ML, very sandy,clay, and caliche, hard,slightly moist, yel.br. 10YR5/6
4		13.5	17.5	15.0	16.5	15.0	16.5		16/23/25	CL, sandy clay w/occ. thin sand lenses, and caliche hard, moist, yel. br. 10YR5/4
5		17.5	26.5	20.0	21.5	20.0	21.5		10/23/37	Clayshale, hard,blocky-crumbly w/occ. oxidized streaks, moist,olive gray 5Y4/2 waxey
6	6/15/81			22.5	24.7	24.2	24.7	Pitcher		Clayshale (Cont. from above) lt. olive br. (2.5Y5/6) and grayish brown (no color code)
7				24.7	26.7	26.2	26.7			
8		26.5	33.5	26.7	29.0	28.5	29.0			Clayshale, silty w/minor very fine sand,hard,blocky-crumbly,oxidized,moist, Olive yel.2.5Y6/6-6/8 (brown in bot. 1½')
9				29.0	31.0	30.5	31.0			
10				31.0	33.3	32.8	33.3			

Sheet 1 of 3 Sheets

Boring No. 1188 Project: RMA Date: 5/22/81 Location: 36
Drill Rig: Failing 1500 Inspector: R.Hunt Operator: B.Harried/D.Taylor Other: E-1

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
11		33.5		33.3	35.3	34.8	35.3			Clayshale, hard, waxey,
12				35.3	37.7	37.2	37.7			massive, blocky, oxidized
13				37.7	40.0	39.5	40.0			along bedding & fractures,
14				40.0	42.2	41.7	42.2			moist, olive (5Y5/4)& olive
										gray
15			48.0	42.2	44.7	44.2	44.7			(5Y4/2)
16		48.0		44.7	47.0	46.5	47.0			Sand, very fine-fine w/occ.
17	6/16/81			47.0	49.3	48.8	49.3			clay lenses, compacted, wet
18				49.3	51.6	51.1	51.6			olive yel. to lt olive br.
19			51.8	51.6	54.0	53.5	54.0			2.5Y6.6-5/6
20		51.8		54.0	56.4	55.9	56.4			Clayshale, thinly bedded w/
										num. thin silt & very fine
										sand lenses & partings, hard
										platey, oxidized along bed-
										ding, moist, olive & olive
										gray
21			53.8	56.4	58.6	58.1	58.6			5Y5/4-4.2
22		53.8		58.6	61.0	60.5	61.0			Clayshale, hard,massive,waxey
23				61.0	63.4	62.9	63.4			blocky-crumbly,occ.slicken-
24				63.4	65.0	64.5	65.0			sides, moist, very dk gray
25				65.0	57.2	66.7	67.2			5Y3/1
26				67.2	69.6	69.1	69.6			(62.0-63.1) organic, black,
										5Y2.5/1. Also
27			70.0	69.6	72.0	71.5	72.0			organic in bot. 0.5'
28		70.0		72.0	74.5	72.0	74.5	Left spt in	tube	Sand, very fine-fine,tightly
										compacted, clean, w/occ.

Sheet 2 of 3 Sheets

Boring No. 1188 Project: RMA Date: 5/22/81 Location: 36

Drill Rig: Failing 1500 Inspector: R.Hunt Operator: B.Harried/D.Taylor Other: E-1

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
28 continued										organic partings and lenses, wet, gray-
29			76.7	74.5	76.7	76.2	76.7			dk gray, 5Y5/1-4/1
30		76.7		76.7	79.0	78.5	79.0			Lignite to highly organic clayshale, hard, flakey, occ slickensides, moist,
			79.0							very dk. br. 10YR2/2
		79.0								Clayshale, hard, blocky, occ. organic imprints, moist,
31			82.0	79.0	81.2	80.7	81.2			very dk gray, 5Y3/1
		82.0								Lignite, w/coal lenses, hard
32			83.0	81.2	83.0	82.5	83.0			blk, 10YR2/1
										Bot. depth 83.0
										Reamed hole to 85.0

Sheet 3 of 3 Sheets

Boring No. 1228 Project: RMA Date: 4/15/82 Location: 36

Drill Rig: Mobile B-53 Inspector: R.Hunt Operator: B.Harried Other: AP-1

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	4/15/82	0.0		0.0	1.5	0.0	1.5	Augar		ML, sdy silt, non-cohesive,
			2.0							slightly moist, dk yel br. 10yr4/4
2		2.0		4.0	5.5	4.0	5.5	2" split-spoon	10-11-13	ML-SM, sdy silt-silty,sd., firm, nun. caliche veinlets, slightly moist, lt yel. br.
3			7.5	9.0	10.5	9.0	10.5		8-16-16	10yr6/4
		7.5								sc, clayey sand, firm, occ small grav. very moist,yel. br. 10yr5/6
4			13.0	14.0	15.3	15.0	15.3		17-55-40/	becomes wet in bot 2-3 ft.
		13.0						Denver	.3	sp, (fine sand) homo, non-cohesive-slightly cohesive wet, olive, 5y4/4 chemical odor
5				19.0	20.0	19.0	20.0		55-120/5	Sp (as above) very strong
6			26.0	24.0	24.5	24.0	24.5		90/0.5	odor (chemical) saturated
7		26.0		29.0	29.5	29.0	29.5	Hammer un-	150/0.5	Sp (as above) but color is
8			32.0	34.0	35.5	34.0	35.5	derwater added pipe to put ham. above H_2O.	25-60-48	olive yel.(possibly checmical coloring above) (2.5y6/6)
		32.0								Clayshale, hard,waxey-silty, very moist,lt. olive br.

Sheet 1 of 4 Sheets

Boring No. 1228	Project: RMA	Date: 4/15/82	Location: 36
Drill Rig: Failing	Inspector: R.Hunt	Operator: B.Harried	Other: AP-1

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
9	4/29/82		37.8	37.0	39.2	38.7	39.2	3" Pitcher		2.5Y5/4, -5/6
		37.8								clayshale,hard,blocky-waxey,
10				39.2	41.5	41.0	41.5			oxidized,moist,occ. sandy silt lenses, gray brown to
11				41.5	43.8	43.3	43.8			lt yel. brown, 2.5y5/2,-6/4, to olive, 5y4/4
12			46.0	43.8	46.1	45.6	46.1			--46.0'--base of oxidation
		46.0								clayshale, hard,blocky,waxey,
13				46.1	48.4	47.9	48.4			in top half, silty in bot. half and organic w/num.
14				48.4	50.5	50.0	50.5			white mineral specks, moist,very dk gray 7.5yr3/0,
			50.3							-10yr3/1
15		50.3		50.5	51.3	50.8	51.3			Coal-high grade lignite, hard,blocky, w/occ. scat.
16				51.3	53.5	53.0	53.5			lt. brown sandy clay lenses,
17				53.5	55.7	55.2	55.7			moist, black, 2.5yr2/0-
18			57.2	55.7	57.8	57.3	57.8			10yr2/1
		57.2								Clayshale, hard,blocky,moist,
19				57.8	60.0	59.5	60.0			occ. organic inclus,dk.gray,
			59.5							7.5yr4/0
20		59.5		60.0	62.3	61.8	62.3			Siltstone,clayey,w/occ. fine silty sand lenses,
21			62.2	62.3	64.6	64.1	64.6			very moist-wet,hard-blocky, gray 7.5yr5/0

Sheet 2 of 4 Sheets

Boring No. 1228 Project: RMA Date: 4/15/82 Location: 36

Drill Rig: Failing Inspector: R.Hunt Operator: B.Harried Other: AP-1

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
		62.2								Sand, fine,homo,compacted,
22			66.6	64.6	66.6	66.1	66.6			saturated, gray,7.5yr6/0
23		66.6		66.6	68.6	68.1	68.6			Clayshale,hard,blocky,occ.
										scat. silty sand/lenses, occ.
24			69.2	68.6	70.5	70.0	70.5			s'sides, moist,dk gray,
										7.5yr4/0
25		69.2		70.5	72.7	72.2	72.7			Sand,fine,homo,massive,
26				72.7	75.2	72.7	75.2	-Left spl in tube		compacted saturated,
27				75.2	77.2	76.7	77.2			occ. thin clayshale lenses
28				77.2	79.4	78.9	79.4			& layers, gray 7.5yr6/0
29			81.5	79.4	81.5	81.0	81.5			(dk green in bot+ 2 ft)
30		81.5		81.5	83.5	83.0	83.5			Clayshale, hard,blocky-crumbly,
31				83.5	85.5	85.0	85.5			num. s'sides, moist, organic
32				85.5	87.5	87.0	87.5			below 87.6'; very dk gray
										2.5y3/0,
33				87.5	90.1	89.6	90.1			-10yr3/1
34				90.1	92.3	91.0	92.3			(86.5-87.6), sdy w/num.
35				92.3	94.4	93.9	94.4			rounded clay balls up to
36	4/30/82		93.0	94.4	96.6	96.1	96.6			1/4" insize, (dk green)
37		93.0		96.6	98.7	98.2	98.7			Sand, fine-med. homo
38				98.7	101.8	101.3	101.8			massive, scat. clayshale
39				101.8	103.8	103.3	103.8			inclus & lenses in top
40				103.8	105.8	103.8	105.8	-Left spl in table		5-6'; compacted, saturated
41				105.8	107.8	107.3	107.8			gray 7.5yr5/0

Sheet 3 of 4 Sheets

Boring No. 1228 Project: RMA Date: 4/15/82 Location: 36

Drill Rig: Failing Inspector: R.Hunt Operator: B.Harried Other: AP-1

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
42				107.8	110.0	109.5	110.0			Sand (cont.)
43				110.0	112.3	111.8	112.3			NOTE: Drilling characteristics
44				112.3	114.5	114.0	114.5			and geo.phy. log, indicates good water sand between 93.0
			121.5	114.5	121.5	-Rock	Bit			and 162.0'
45		121.5	126.0	121.5	122.0	121.5	122.0	-Very hard sandstone		Sandstone, very hard
		126.0	162.0	122.0	170.0	-Rock	Bit			Sand (as above) (145.0-152.0) sand is clayey, according to geo.phy. log.
		162.0	170.0							Clayshale Bot. Depth - 170.0'

Sheet 4 of 4 Sheets

Boring No. 1247 Project: ____ Date: 4/12/82 Location: RMA
Drill Rig: Mobile B-53 Inspector: R.Hunt Operator: B.Harried Other: AP-2T

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	4/12/82	0.0		0.0	1.5	0.0	1.5	Augar		SM-ML, sdy,silt-silty sd. non-cohesive, moist, dk. yel. brown, 10yr4/4
			2.5							
2		2.5		4.0	5.5	4.0	5.5	2"split-spoon		SP, fine sand, non-slightly cohesive slightly moist, very pale brown, 10yr7/4, w/minor silt
3				9.0	10.5	9.0	10.5		8-9-12	SP (as above) but more moist-ure, lt yel.br 10yr6/4
			13.5							
4		13.5		14.0	15.5	14.0	15.5	Denver 3"Pitcher	16-30-42	Vocaniclastic sediments,clayey matrix,w/60%+ sand size, rounded to
5	5/25/82			17.5	19.5	19.0	19.5			
6				19.5	21.5	21.0	21.5			angular rock fragments and occasional rock
7				21.5	23.5	23.0	23.5			frag. up to 2"+ size,hard, blocky
8				23.5	25.6	25.1	25.6			oxidized,moist-very moist,dk
9			32.0	25.6	27.8	27.3	27.8			gray br 2.5y4/2-yel.br.10yr5/6
10		32.0		27.8	29.9	29.4	29.9			clayshale,hard,waxey,blocky-
11				29.9	31.9	31.4	31.9			crumbly oxidized,moist,olive
12			44.8	31.9	34.2	33.7	34.2			5y5/3-4/3 olive gray-5y4/2
13		44.8		34.2	36.3	35.8	36.3			Clayshale,organic,hard,blocky-
14				36.3	38.5	38.0	38.5			crumbly,thinly bedded,occ.thin
15				38.5	40.3	39.8	40.3			lt.br. sdy clay lenses(micaeous)
16			46.6	40.3	42.5	42.0	42.5			moist,dk gray-v.dk gray br. 10yr4/1-3/2

Sheet 1 of 6 Sheets

Boring No. 1247 **Project:** **Date:** 4/12/82 **Location:** RMA
Drill Rig: Failing (WES) **Inspector:** R.Hunt **Operator:** D.Taylor **Other:** AP-21

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
17		46.6		42.5	45.0	44.5	45.0			Siltstone,Clayey,micaeous,mod.
18				45.0	47.3	46.8	47.3			hard,blocky,oxidized along
19				47.3	49.3	48.8	49.3			frac.moist-vy moist,num.organic
			48.8							inclus. gray-olive gray,5y5/1-
		48.8								4/2 Siltstone,sandy-clayey,occ.
20				49.3	51.4	50.9	51.4			clay partings and sm.clay fill worm borings, occ.organic inclus. mod.hard (weakly bond) oxidized very moist,lt yel.br-
			51.6							olive yel. 2.5y6/4,-6/6
21		51.6		51.4	53.6	53.1	53.6			Sand,fine-med.very tightly com-
			53.4							pacted,micaeous,thinly bedded w/occ. clay partings & inclus. occ. organic partings,oxidized,
22		53.4		53.6	55.7	55.2	55.7			very moist-wet,color as above. Clayshale,hard,blocky-crumbly, num.s'sides,oxidized along frac. occ.organic inclus,moist,
23			57.2	55.7	57.7	55.2	57.7			Very dk gray 10yr3/1-dk gray,
		57.2								10yr4/1 Sand,fine,homo,massive
24				57.7	59.8	59.3	59.8			widely scat. thin clayshale
								Saved spl AP-21 58.0-	tube in 60.5	lenses and partings, tightly compacted,wet-saturated
25			61.5	59.8	62.0	61.5	62.0			oxidized, lt.olive br.2.5y5/6
26		61.5		62.0	64.2	63.7	64.2			Clayshale,hard,blocky-platey

Sheet 2 of 6 Sheets

Boring No. 1247 **Project:** **Date:** 4/12/82 **Location:** RMA
Drill Rig: Mobile B-53 **Inspector:** R.Hunt **Operator:** D Taylor **Other:** AP-21

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
27				64.2	66.4	65.9	66.4			thinly bedded w/num silty
28				66.4	68.6	68.1	68.6			partings and occ.fine silty
29	5/26/82			68.6	70.6	70.1	70.6			sand lenses up to 0.5" thick
30				70.6	72.6	72.1	72.6			occ. high angle s'side,oxidized
31				72.6	74.9	74.4	74.9			along bedding & frac.organic
32			77.0	74.9	77.0	76.5	77.0			inclus. along bedding,moist dk gray 5y4/1 (73.5-74.0)
33		77.0		77.0	79.0	78.5	79.0			(fine silty sand),wet 77.0-base of oxidation Clayshale,hard,blocky, occ. organic inclus,moist,vy dk gray
34		79.2	79.2	79.0	81.2	80.7	81.2			5y3/1, occ. s'sides Organic-lignitic clayshale,hard platey,moist,black 5y2.5/1 2.5y2/0
35		81.5	81.5	81.2	83.3	82.8	83.3			Clayshale,silty,hard,blocky, moist-very moist dk gray 5y4/1
36		82.5	82.5	83.3	85.3	84.8	85.3			Sand,fine,med. tightly com-pacted,num lignite partings & lenses,wet,gray 5y5/1
37		86.0	86.0	85.3	87.0	86.5	87.0			Clayshale,hard,blocky-crumbly num. of s'sides, organic in
38			89.0	87.0	89.2	88.7	89.2			top 0.5'±, silt and fine sand lenses in bot. ft(±),vy dk 2.5y3/0

Sheet 3 of 6 Sheets

Boring No. 1247 Project: Date: 4/12/82 Location: RMA

Drill Rig: Mobile B-53 Inspector: R.Hunt Operator: D.Taylor Other: AP-21

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
39		89.0		89.2	91.1	90.6	91.1			Sand,fine-med,tightly,com- pacted,occ. organic partings,
40			91.1	91.1	93.5	93.0	93.5			wet, gray 5y5/1
41		91.1		93.5	95.7	95.2	95.7			Clayshale,hard,crumbly-blocky
42				95.7	98.0	97.5	98.0			num, s'sides,moist-very
43				98.0	100.2	99.7	100.2			moist,dk gray green-green gray
44			101.5	100.2	102.5	102.0	102.5			(no color code)
		101.5								Sandstone,clayey,mod.hard,
45				102.5	105.0	104.5	105.0			(weakly bonded)num.organic partings,thinly bedded
46				105.0	107.3	106.8	107.3			(clayey matrix)moist dk green gray,numerous
47				107.3	109.6	109.1	109.6			rounded "clay sand grains", fine-med.except in bot.ft is
48				109.6	111.7	111.2	111.7			med.coarse w/rounded hard
			110.0							clay balls 1/4"+ in size
49		110.0		111.7	114.0	113.5	114.0			Highgrade lignite-coal, hard, platey-flakey (less coal like than is normal for this sec.
50				114.0	115.7	115.2	115.7			in other borings)occ.lt.br. micaeous,sdy clay lenses especially in bot.of sect. (below sand)
51				115.7	118.0	117.5	118.0			moist-very moist;very dk gray-black-5yr3/1,-2.5/1

Sheet 4 of 6 Sheets

Boring No. 1247 Project: ______ Date: 4/12/82 Location: RMA

Drill Rig: Mobile B-53 Inspector: R.Hunt Operator: D.Taylor Other: AP-21

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
			118.2							to 7.5yr2/0 Note:(113.6-114.6) gray clayshale in top half of this 1' zone changing to gray, wet fine sand in bot. half-beginning of separation in coal bed as seen in SP5 AP-17 etc. & other borings to the west & southwest of AP-21.
52		118.2		118.0	120.2	119.7	120.2			Siltstone, fine sand, w/organic inclus. weakly bonded, blocky platey very moist-wet gray
53			122.5	120.2	122.5	122.0	122.5			5y5/1
		122.5								siltstone, clayey, thinly bed-
54				122.5	125.0	124.5	125.0			ded, (similar to above) but
			125.5							less sand)
55	5/27/82	125.5		125.0	127.2	126.7	127.2			clayshale, hard, blocky-crumbly
56				127.2	129.5	129.0	129.5			num. s'sides, moist, very dk
57			130.8	129.5	131.5	131.0	131.5			green gray
		130.8								sandstone (similar to zone
58			133.5	131.5	133.5	133.0	133.5			between (101.5 & 110.0')
										133.5 - bot. depth. poured gravel in'. from 100.0 to 133.5 sealed hole with

Sheet 5 of 6 Sheets

Boring No. 1247 Project: Date: 4/16/82 Location: RMA

Drill Rig: Mobile B-53 Inspector: R.Hunt Operator: D.Taylor Other: AP-21

Sample Number	Date Taken	Stratum		Drive		Sample		Type of Sampler	Blow Counts	Classification and Remarks
		From	To	From	To	From	To			
										bentonite from 96.0 to 100.0 set piez above 96.0'

Sheet 6 of 6 Sheets

Boring No. 1251 **Project:** RMA **Date:** 4/16/82 **Location:**
Drill Rig: Failing **Inspector:** R.Hunt **Operator:** D.Taylor **Other:** AP-25

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
1	4/16/82	0.0		0.0	1.5	0.0	1.5	Auger		<u>ML-SM</u>-sdy silt-silty-sd-non-cohesive, slightly moist, yel. br. 10YR5/4
2		2.0	2.0	4.0	5.5	4.0	5.5	2"split-spoon	9/7/15	<u>sp</u>, very fine sd,non-cohesive
3			12.0	9.0	10.5	9.0	10.5	2"split-spoon	8/13/31	slightly moist, yel. br. 2.5 Y5/6-2.5Y5/8
4		12.0	15.5	14.0	15.1	14.0	15.1	2"split-spoon	25/63/25/0.1	<u>Volcaniclastic sediments</u> (cal-<u>iclie filling fractures</u> in upper 2-3')
5	5/4/82	15.5		17.0	19.2	18.7	19.2	3" Pitcher		<u>Clayshale</u>, hard,waxey,blocky crumbly,oxidized along fractures occ.organic inclus.,moist, olive gray 5Y4/2 to gray br 2.5Y5/2
6				19.2	21.3	20.8	21.3			
7				21.3	23.4	22.9	23.4			
8				23.4	25.8	25.3	25.8			
9				25.8	28.0	27.5	28.0			
10				28.0	30.0	29.5	30.0			(33.5-37.0)-silty, dk brown 7.5Y3/2-3.4
11			37.0	30.0	32.3	31.8	32.3			
12				32.0	34.7	34.2	34.7			
13		37.0		34.7	37.0	36.5	37.0	3" Pitcher		<u>Sandstone</u>, weakly bonded, <u>fine in top half</u>, medium in bot. half, num angular sub-angular rock fragments in top half, oxidized, wet br. yel to yel br. 10YR6/8 - 5/8
14				37.0	39.2	38.7	39.2			
15			41.5	39.2	41.4	40.9	41.4			
16		41.5		41.4	43.6	43.1	43.6			<u>Clayshale</u>, organic, hard, blocky

Sheet 1 of 4 Sheets

Boring No. 1251	Project: RMA	Date: 4/16/82	Location:
Drill Rig: Failing	Inspector: R.Hunt	Operator: D. Taylor	Other: AP-25

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
17				43.6	45.6	45.1	45.6			moist-very moist, dk. br.
18			43.0	45.6	47.8	47.3	47.8			7.5yr3/2
19		43.0		47.8	50.0	49.5	50.0			Clayshale, hard, blocky, num.
20				50.0	52.0	51.5	52.0			organic inclus., occ.
										slickensides
21				52.0	54.0	-----	-----	Tube empty		moist, olive, 5y5/3 and dk.
22			47.8	54.0	55.2	54.0	55.2	Left spl. in tube		gray, 5Y4/1
23		47.8		55.2	57.4	56.9	57.4			sand, fine, homo, massive
24				57.4	59.5	59.0	59.5			tightly compacted,saturated,
25				59.5	61.5	61.0	61.5			lt. olive br. 2.5y5/6
26				61.5	63.7	63.2	63.7			sand (cont.)
27				63.7	66.0	65.5	66.0			(sand is med. grained
28	5/5/82			66.0	68.0	67.5	68.0			in bot 15± ft)
29				68.0	70.2	69.7	70.2			
30				70.2	72.5	72.0	72.5			
31				72.5	74.8	74.3	74.8			
32				74.8	77.0	76.5	77.0			(80.5-81.5) color changes
33				77.0	78.2	77.7	78.2			to gray green.
34			81.5	78.2	80.5	80.0	80.5			
35		81.5		80.5	82.8	82.3	82.8			Clayshale, hard, blocky,
										organic inclus. along with
36				82.5	85.4	84.9	85.4			num s' sides in top half,
										moist, block, 5y2.5/1,
										changing to greenish gray
37			87.5	85.4	87.5	87.0	87.5			toward bot.

Sheet 2 of 4 Sheets

Boring No. 1251 **Project:** RMA **Date:** 4/16/82 **Location:**

Drill Rig: Failing **Inspector:** R.Hunt **Operator:** D.Taylor **Other:** AP-25

Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
38		87.5		87.5	89.8	89.3	89.8			Sand, very fine-fine,homo
39				89.8	92.2	91.7	92.2			massive,saturated,tightly
40			92.5	92.2	94.5	94.0	94.5			compacted, gray 2.5y6/0-5/0
41		92.5		94.5	96.5	96.0	96.5			Clayshale, hard-very hard,
42				96.5	98.7	98.2	98.7			blocky, alternating zones
43				98.7	101.0	100.5	101.0			w/num. s'sides, scattered
44				101.0	103.2	102.7	103.2			organic inclus., color
45				103.2	105.2	104.7	105.2			varies from dk gray
46				105.2	107.4	106.9	107.4			5y3/1-10yr3/1, and
47				107.4	109.6	109.1	109.6			dk gray green (no color code)
48				109.6	111.8	111.3	111.8			(97.0-98.0) num. organic
49	5/6/82		113.9	111.8	114.0	113.5	114.0			inclusions.
50		113.9		114.0	116.3	115.8	116.3			Coal-High grade lignite,
51				116.3	117.3	116.8	117.3			hard, blocky-platey, w/
52				117.3	119.4	118.9	119.4			occ. lt. br. micaeous sdy
										clay lenses, moist,
53			120.5	119.4	121.6	121.1	121.6			black, 2.5yr2/0
54		120.5		121.6	123.8	123.3	123.8			Sandstone, weakly bonded,
										very fine-fine, w/alternating
55				123.8	126.0	125.5	126.0			lense and layers of clayshale,
										Sandstone is massive, mod.
56				126.0	128.1	127.6	128.1			hard, wet & gray, 5y5/1 claysh
57				128.1	130.2	129.7	130.2			blocky, moist and dk.
58				130.2	132.5	130.2	132.5	(-Left spl	in tube)	gray, 5y3/1 silty, hard
										(123.1-125.4) clayshale

Sheet 3 **of** 4 **Sheets**

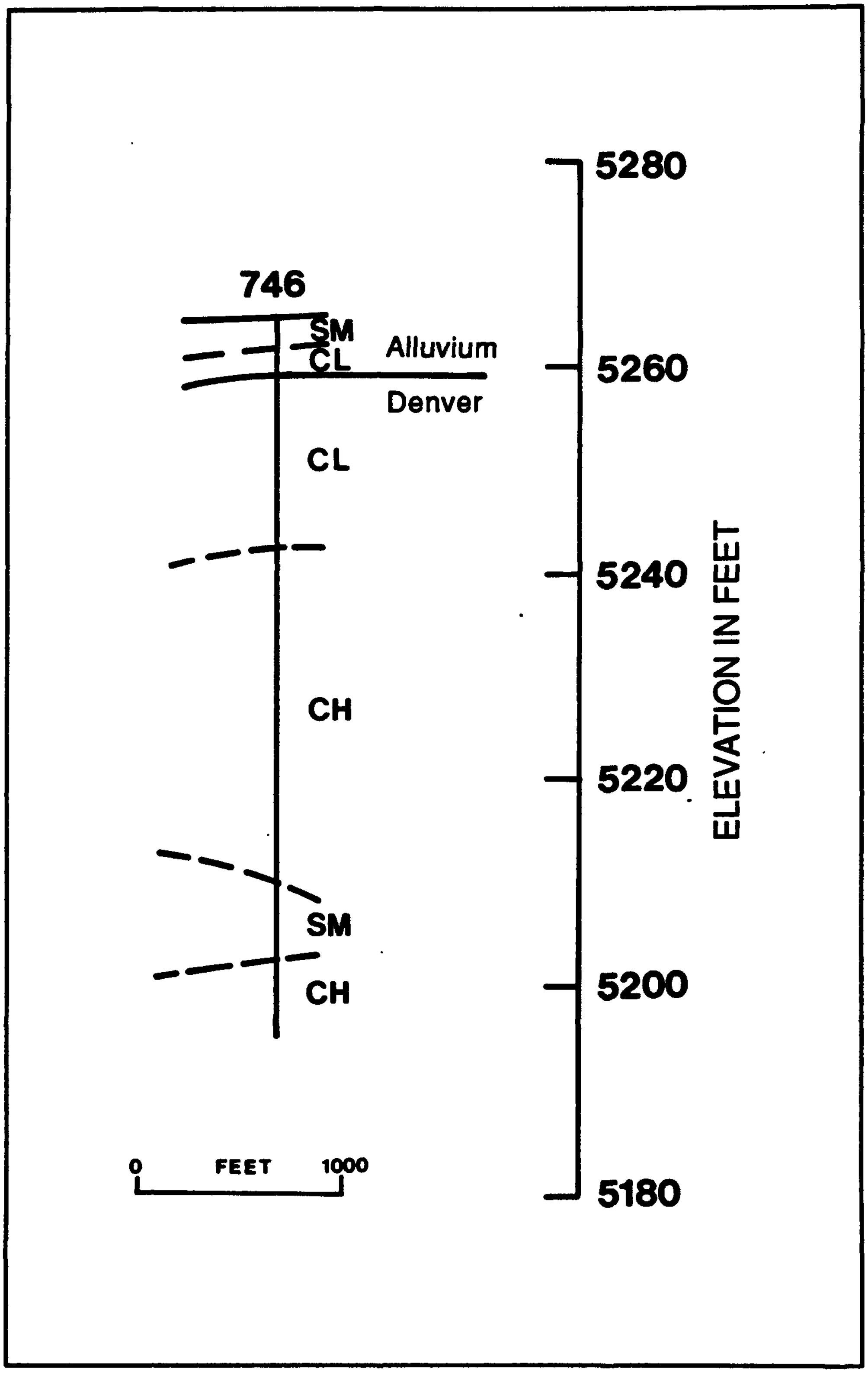
Boring No. 1251 Project: RMA Date: 4/16/82 Location:

Drill Rig: Failing Inspector: R.Hunt Operator: D.Taylor Other: AP-25

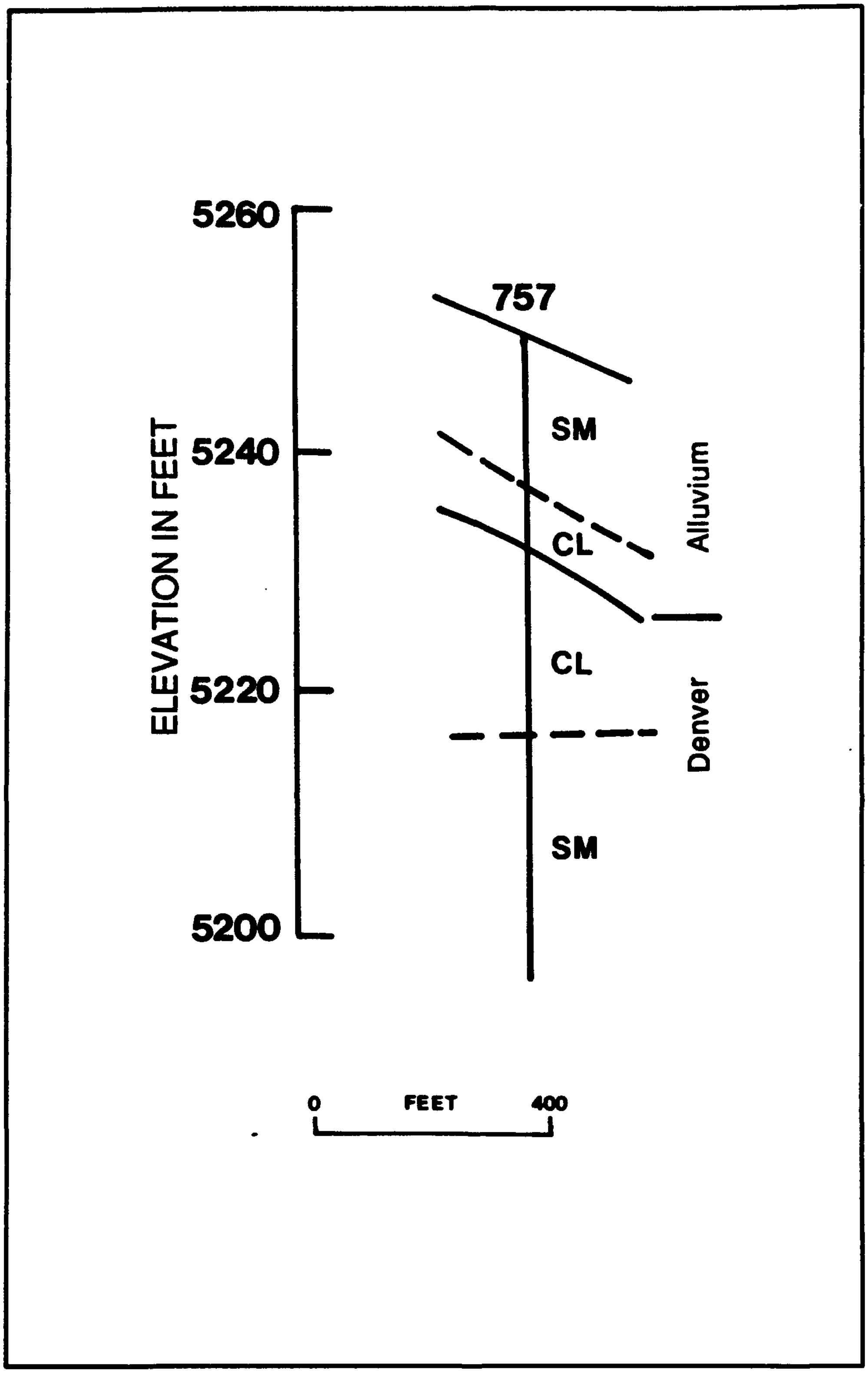
Sample Number	Date Taken	Stratum From	Stratum To	Drive From	Drive To	Sample From	Sample To	Type of Sampler	Blow Counts	Classification and Remarks
59			128.3	132.5	134.8	134.3	134.8			(as above)
		128.3								Sand, fine in upper 2-3' changing to med. grained w/ depth, massive, tightly compacted, saturated, dk gray, 5y4/1
60				134.8	137.0	136.5	137.0			
61				137.0	139.2	138.7	139.2			
			139.5							
62				139.2	141.4	140.9	141.4			
63		139.5		141.4	143.5	143.0	143.5			Clayshale, hard, thinly bedded w/thin silt lenses and partings from 139.5 to 142.0' blocky in bot, w/num. small white mineral specks from 142.0-142.9', moist very dk grey to black. 7.5yr3/0,-2/0
			143.5							
										Reamed hole to 144.0' bot depth -144.0'

Sheet 4 of 4 Sheets

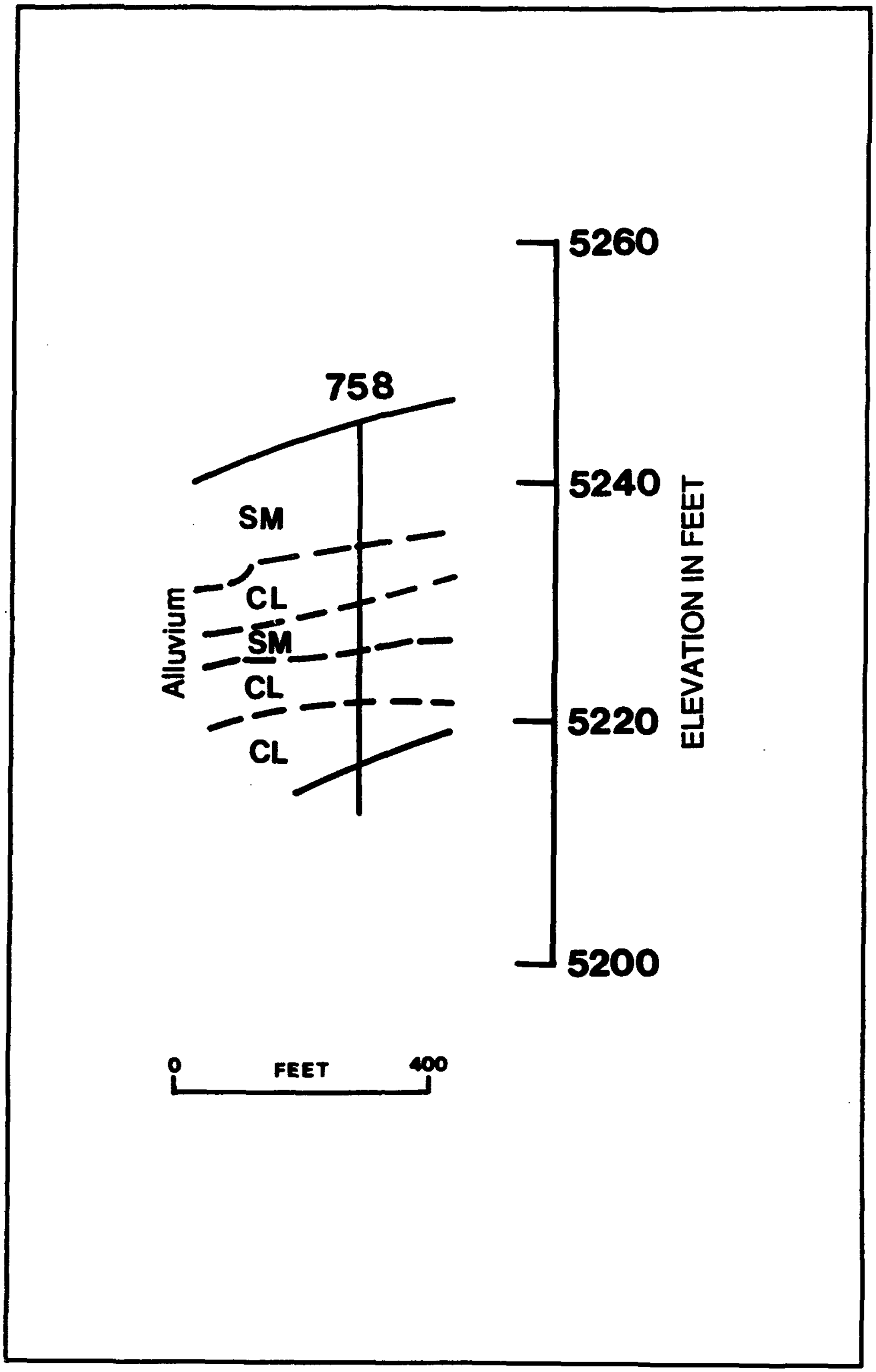
Appendix H
Cross Sectional and Tabular Stratigraphic Information



Cross-sectional information for boring 746 (from Braughton et al. 1979)



Cross-sectional information for boring 757 (from Braughton et al. 1979)



Cross-sectional information for boring 758 (from Braughton et al. 1979)

Tabular Data for all Wells in the Rocky Mountain Arsenal Study Site (after Ebasco et al. 1989)

Boring #	Section and Well #	Zone or Unit	Sandstone Top Elevation, ft	Sandstone Base Elevation, ft	Sandstone Thickness, ft
	01005	AS	5201.6	5174.6	27.0
	01005	AU	5211.6	5204.6	7.0
722	01008	AL	5181.2	5176.2	5.0
722	01008	AM	5209.9	5190.7	19.2
746	01015	AU	5216.5	5206.1	10.4
748	01017	AM	5182.6	5177.5	5.1
748	01017	AU	5193.7	5183.1	10.6
1143	01022	AM	5154.5	5147.5	7.0
1143	01022	AU	5171.5	5162.9	8.6
1143	01023	1U	5107.0	5095.0	12.0
1155	01025	AU	5173.9	5166.9	7.0
1155	01026	AL	5152.4	5146.9	5.5
1154	01028	AS	5197.2	5190.2	7.0
1154	01028	AU	5206.1	5202.2	3.9
1154	01029	AL	5156.2	5142.7	13.5
1154	01029	AM	5184.7	5181.7	3.0
1162	01031	AU	5208.1	5206.2	1.9
1162	01032	AM	5184.0	5177.6	6.4
1157	01034	AM	5174.0	5168.6	5.4
1157	01034	AU	5193.5	5192.2	1.3
1157	01035	AL	5162.0	5156.5	5.5
1236	01036	AU	5202.9	5201.6	1.3
1236	01037	AL	5161.9	5160.6	1.3
1236	01037	AM	5172.6	5165.8	6.8
1237	01039	AU	5192.9	5191.4	1.5
1237	01040	AL	5165.0	5157.1	7.9
1237	01040	AM	5173.4	5170.3	3.1
1238	01042	AL	5171.2	5168.8	2.4
1238	01042	AU	5202.2	5201.0	1.2
1238	01043	1	5112.0	5106.8	5.2
	01046	2	0.0	0.0	49.0 Est.
1240	01047	1	5093.8	5074.0	19.8
1240	01047	1U	5114.9	5107.6	7.3
1240	01047	AL	5157.8	5156.3	1.5
1240	01047	AM	5185.6	5182.6	3.0
1240	01047	AU	5192.3	5189.3	3.0
1240	01048	2	5070.0	5045.3	24.7
1241	01050	AS	5203.4	5157.4	46.0
(AP29)	01067	AS	5199.0	5160.1	38.9
(AP29)	01067	AU	5218.0	5208.9	9.1
	01068	VC	5283.9	5238.6	45.3
	01071	1	5092.6	5078.7	13.9
	01071	1U	5129.1	5118.6	10.5
	01071	2	5075.1	5070.6	4.5
	01071	AL	5174.6	5172.1	2.5

Tabular Data for all Wells in the Rocky Mountain Arsenal Study Site (after Ebasco et al. 1989)

Boring #	Section and Well #	Zone or Unit	Sandstone Top Elevation, ft	Sandstone Base Elevation, ft	Sandstone Thickness, ft
	01071	AM	5186.1	5185.1	1.0
	01071	AU	5200.5	5195.1	5.4
705	02004	AS	5208.1	5162.8	45.3
1122	02009	1	5105.7	5103.7	2.0
1122	02010	2	5086.8	5077.9	8.9
1122	02010	3	5072.9	5044.9	28.0
1124	02012	1U	5114.6	5109.6	5.0
1124	02013	2	5063.6	5048.9	14.7
1123	02015	1U	5149.2	5134.2	15.0
1123	02016	2	5091.7	5075.2	16.5
1128	02018	AU	5221.4	5208.7	12.7
1128	02019	1U	5165.0	5159.0	6.0
1128	02019	AL	5187.5	5169.4	8.1
1148	02021	AM	5182.0	5167.4	14.6
1148	02022	1U	5138.3	5125.5	12.8
1148	02022	AL	5154.0	5143.0	11.0
1153	02024	AL	5178.3	5177.2	1.1
1153	02024	AM	5191.1	5186.2	4.9
1158	02027	AL	5153.4	5142.9	10.5
1158	02027	AM	5160.2	5156.6	3.6
1158	02028	1U	5117.4	5103.7	13.7
1161	02030	AL	5177.9	5176.0	1.9
1161	02030	AM	5196.4	5195.0	1.4
1161	02030	AU	5219.6	5208.3	11.3
1161	02031	1U	5135.5	5128.6	6.9
1242	02032	AU	5190.1	5181.9	8.2
1242	02033	1U	5127.2	5102.6	24.6
1243	02035	AL	5180.0	5177.8	2.2
1243	02035	AM	5197.5	5191.9	5.6
1243	02035	AU	5207.0	5202.5	4.5
1244	02038	AM	5204.1	5190.6	13.5
1244	02039	1U	5154.0	5147.0	7.0
1244	02039	AL	5175.9	5159.7	16.2
1246	02041	AL	5179.2	5167.7	11.5
1246	02041	AM	5200.0	5197.0	3.0
1246	02042	1U	5164.0	5143.5	20.5
1247	02043	AU	5216.1	5206.2	9.9
1247	02044	1U	5149.2	5134.2	15.0
1247	02044	AL	5185.2	5176.6	8.6
1248	02045	AL	5195.1	5184.0	11.1
1248	02045	AM	5206.6	5194.1	12.5
1248	02045	AU	5227.1	5217.6	9.5
1248	02046	1U	5154.6	5128.9	25.7
1249	02047	AS	5218.7	5174.7	44.0
1249	02048	1U	5138.7	5136.0	2.7

Tabular Data for all Wells in the Rocky Mountain Arsenal Study Site (after Ebasco et al. 1989)

Boring #	Section and Well #	Zone or Unit	Sandstone Top Elevation, ft	Sandstone Base Elevation, ft	Sandstone Thickness, ft
6	35001	1U	5165.0	5153.0	12.0
139	35004	AL	5178.0	5172.5	5.5
17	35005	1U	5168.0	5148.0	20.0
15	35006	1U	5159.0	5133.0	26.0
650	35009	1U	5175.0	5156.0	19.0
650	35009	AL	5197.0	5181.0	16.0
649	35010	1	5148.0	5142.0	6.0
145A	35012	1	5145.0	5129.3	15.7
145A	35012	1U	5163.0	5156.0	7.0
702	35015	AU	5213.4	5212.0	1.4
723	35016	1U	5175.0	5156.0	19.0
723	35017	1	5128.0	5122.0	6.0
725	35018	1U	5172.0	5136.0	36.0
725	35019	2	5127.0	5115.0	12.0
726	35021	1U	5163.4	5143.8	19.6
726	35021	AL	5192.5	5181.9	10.6
730	35024	AS	5215.8	5178.0	37.8
732	35027	AL	5173.6	5166.9	6.7
732	35027	AU	5211.1	5204.6	6.5
732	35028	1U	5147.0	5142.0	5.0
757	35030	AS	5210.4	5199.9	10.5
816	35032	1	5143.0	5121.0	22.0
816	35033	1U	5161.0	5143.0	18.0
816	35033	2	5097.0	5091.0	6.0
817	35035	1U	5188.0	5159.0	29.0
817	35036	1	5143.0	5123.0	20.0
818	35038	1	5148.5	5138.5	10.0
818	35039	2	5128.5	5090.0	38.5
819	35041	1	5137.0	5124.0	13.0
819	35041	2	5110.0	5089.0	21.0
822	35042	2	5105.0	5084.0	21.0
771	35045	1U	5169.0	5157.0	12.0
823	35046	1U	5168.4	5152.4	16.0
823	35046	AL	5173.4	5172.4	1.0
651	35051	1U	5173.0	5154.0	19.0
1127	35053	AM	5200.3	5188.3	12.0
1127	35053	AU	5212.3	5205.3	7.0
1127	35054	AL	5195.9	5177.6	18.3
1141	35055	AL	5184.6	5182.2	2.4
1141	35055	AU	5212.9	5205.8	6.1
1141	35055	B	5250.4	5231.4	19.0
1141	35056	1U	5151.0	5127.0	24.0
1145	35059	1U	5162.0	5148.0	14.0
1145	35060	2	5128.0	5121.0	7.0
1147	35062	AL	5179.3	5166.5	12.8

Tabular Data for all Wells in the Rocky Mountain Arsenal Study Site (after Ebasco et al. 1989)

Boring #	Section and Well #	Zone or Unit	Sandstone Top Elevation, ft	Sandstone Base Elevation, ft	Sandstone Thickness, ft
1147	35063	1U	5152.0	5131.0	21.0
1184	35066	AL	5191.0	5174.3	16.7
1184	35067	1U	5169.0	5153.5	15.5
1184	35068	1	5136.0	5115.0	21.0
1184	35068	2	5115.0	5097.0	18.0
1184	35068	3	5093.0	5077.0	16.0
1185	35070	1U	5156.3	5153.2	3.1
1250	35071	1U	5135.7	5114.2	21.5
1250	35071	AS	5209.6	5181.0	28.6
1250	35072	1	5102.3	5093.0	9.3
1251	35073	AS	5209.0	5181.9	27.1
1251	35074	AL	5175.9	5170.9	5.0
	35078	1	5125.0	5120.8	4.2
	35078	1U	5170.0	5156.5	13.5
	35078	2	5108.0	5100.2	7.8
	35081	1	5136.7	5133.7	3.0
	35081	1U	5170.7	5161.4	9.3
	35081	2	5122.7	5101.0	21.7
	35082	1	5112.0	5106.0	6.0
	35082	1U	5147.0	5136.0	11.0
	35082	2	5097.7	5091.0	6.7
	35082	3	5077.1	5044.0	33.1
	35082	AL	5184.0	5182.0	2.0
	35082	AM	5208.0	5200.0	8.0
	35082	AU	5226.0	5224.0	2.0
	35088	1	5119.0	5108.3	10.7
	35088	1U	5166.5	5147.3	19.2
	35089	2	5091.5	5083.0	8.5
	35089	3	5077.5	5046.5	31.0
CP113	36002	AL	5200.5	5197.0	3.5
CP114	36003	AS	5217.8	5211.8	6.0
CP115	36004	AS	5221.6	5218.7	2.9
CP111	36007	AS	5220.3	5214.8	5.5
CP110	36008	AS	5219.2	5202.9	16.3
CP109	36009	AS	5214.9	5210.1	4.8
CP105	36010	AS	5210.5	5201.3	9.2
CP106	36011	AS	5210.9	5201.8	9.1
CP107	36012	AS	5213.6	5210.5	3.1
40	36020	AM	5222.9	5206.9	16.0
CO116	36024	AL	5205.5	5198.7	6.8
RP105	36025	AS	5210.6	5204.4	6.2
RP106	36026	AS	5213.6	5203.6	10.0
RP104	36027	AM	5216.7	5206.7	10.0
RP109	36029	AS	5216.6	5210.8	5.8
AP113	36033	AS	5222.0	5207.0	15.0

Tabular Data for all Wells in the Rocky Mountain Arsenal Study Site (after Ebasco et al. 1989)

Boring #	Section and Well #	Zone or Unit	Sandstone Top Elevation, ft	Sandstone Base Elevation, ft	Sandstone Thickness, ft
RP114	36034	AS	5223.0	5209.0	14.0
CO101	36036	AS	5218.9	5191.5	27.4
CO105	36037	AS	5216.8	5185.5	31.3
CO109	36038	AS	5214.1	5181.1	33.0
CO113	36039	AS	5209.1	5183.9	25.2
CO116	36043	AM	5196.3	5190.0	6.3
CO201	36044	AS	5221.2	5180.3	40.9
707	36061	AL	5182.3	5182.1	0.2
707	36061	AM	5199.9	5191.1	8.8
707	36061	AU	5209.8	5209.6	0.2
708	36062	AL	5174.8	5154.9	19.6
710	36063	AL	5176.8	5159.0	17.8
711	36066	1U	5146.7	5141.3	5.4
711	36066	AL	5169.9	5156.3	13.6
711	36066	AU	5216.8	5206.4	10.4
	36071	AM	5202.5	5193.0	9.5
	36072	AL	5184.8	5170.7	14.1
727	36076	AU	5223.6	5205.4	18.2
734	36078	AS	5214.0	5208.0	6.0
734	36079	1	5142.0	5132.0	10.0
734	36079	1U	5163.0	5158.0	5.0
	36081	1U	5145.0	5140.0	5.0
	36081	AL	5181.7	5166.9	14.8
	36104	AM	5196.5	5176.9	22.6
718	36105	AL	5169.9	5162.2	7.7
718	36105	AM	5186.8	5169.9	16.9
718	36105	AU	5209.2	5201.7	7.5
781	36110	AS	5196.6	5193.5	3.1
1149	36113	AL	5168.0	5167.5	0.5
1149	36113	AM	5201.0	5198.0	3.0
1149	36113	AS	5207.3	5206.3	1.0
1149	36114	1	5146.0	5126.0	20.0
1149	36114	2	5126.0	5100.0	26.0
	36116	AU	5257.8	5244.8	13.0
	36117	AM	5224.3	5209.8	14.5
1160	36118	AU	5209.0	5201.0	8.0
1160	36119	AM	5176.9	5158.6	18.3
1188	36121	AM	5180.6	5174.8	5.8
1188	36122	AM	5158.6	5151.9	6.7
LM01	36147	1U	5162.6	5161.4	1.2
LM01	36147	AL	5212.3	5204.9	7.4
LM01	36147	AM	5219.0	5216.5	2.5
LM01	36147	AU	5224.2[a]	5222.7[a]	1.5
1228	36148	2	5110.0[a]	5090.0[a]	20.0
1228	36148	3	5090.0	5074.0	16.0

Tabular Data for all Wells in the Rocky Mountain Arsenal Study Site (after Ebasco et al. 1989)

Boring #	Section and Well #	Zone or Unit	Sandstone Top Elevation, ft	Sandstone Base Elevation, ft	Sandstone Thickness, ft
1228	36149	1U	5175.0*	5155.0*	20.0
1228	36150	1	5144.0	5110.0	34.0
1228	36150	AS	5223.6	5204.6	19.0
1234	36154	1U	5126.7	5116.3	10.4
1234	36155	AL	5160.1	5156.0	4.1
1234	36155	B	5243.3	5231.3	12.0
1235	36156	1U	5125.0	5117.5	7.5
1235	36156	AL	5155.0	5153.0	2.0
1235	36156	AM	5199.5	5171.2	28.3
	36169	AM	5169.0	5165.0	4.0
	36170	1	5114.0	5095.0	19.0
	36170	1U	5137.0	5134.0	3.0
	36170	2	5095.0	5073.0	22.0
	36170	AL	5158.0	5153.0	5.0
	36179	1	5141.0	5118.0	23.0
	36179	1U	5163.0	5152.0	11.0
	36179	2	5118.0	5090.0	28.0
	36182	AS	5222.0	5174.0	48.0
	36183	AL	5157.0	5143.0	14.0
	36183	AM	5164.0	5162.0	2.0
1242	02032	AL	5170.1	5164.1	6.0

* Approximate

Note: Zone or Unit AS is the "target" sand.

Appendix I
Geophysical Logs

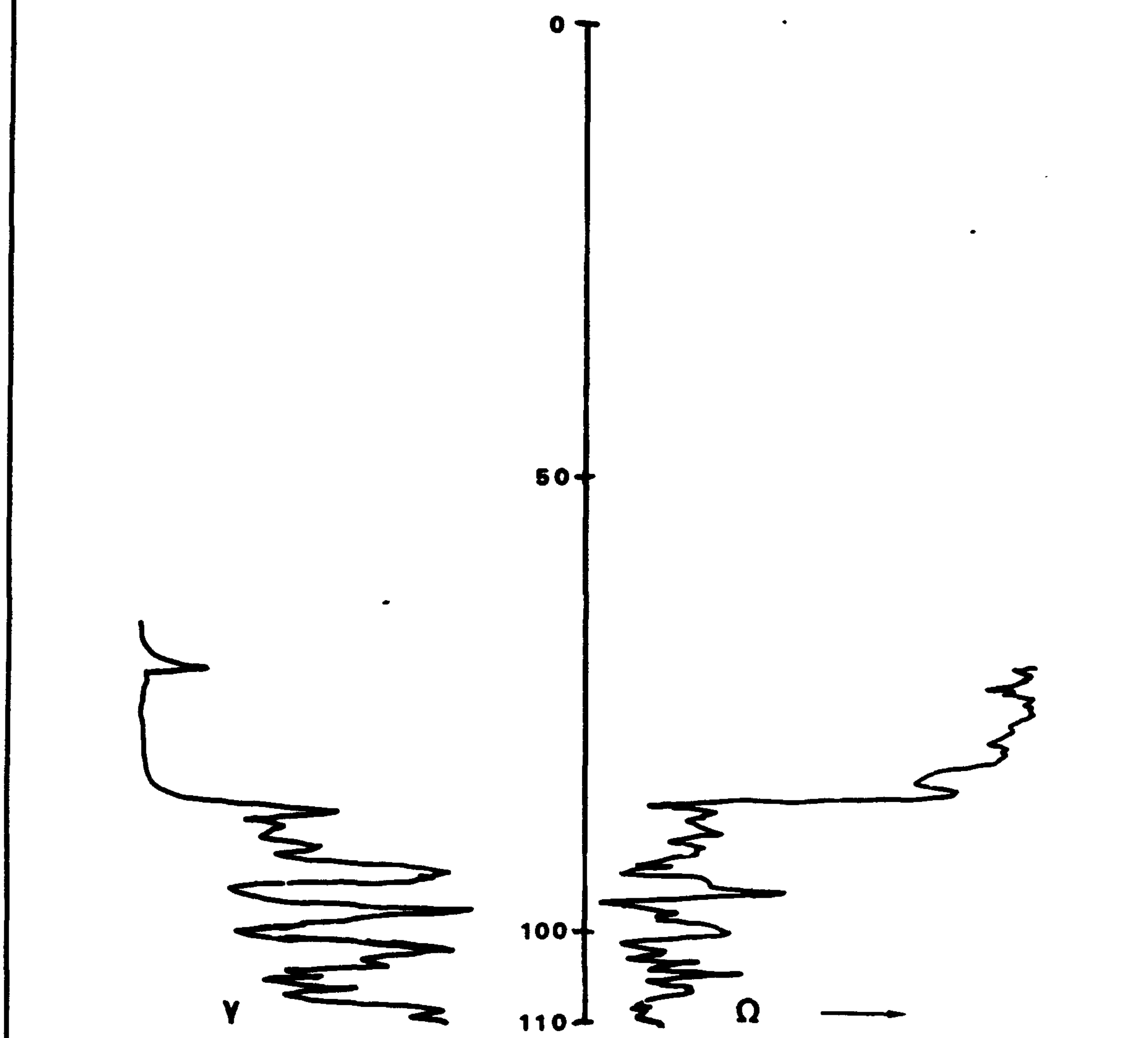
Well Logging Co.: Western Well Logging, Inc.
Client: U.S. Army Corp of Engineers
Hole #: 1123 (SP-8) Date: 18 July, 1980
Location:
Depth Logged: 147' Depth Drilled:
Wire Line Operator: P. O'Brian Unit/Instrument #: L-4
Geologist/Witness: Engineer: Maj Zebell
Fluid Type: Fluid Level: Time Since Circulation:
Bit Size: Cased Interval:
Inside Casing Diameter: Casing Thickness:

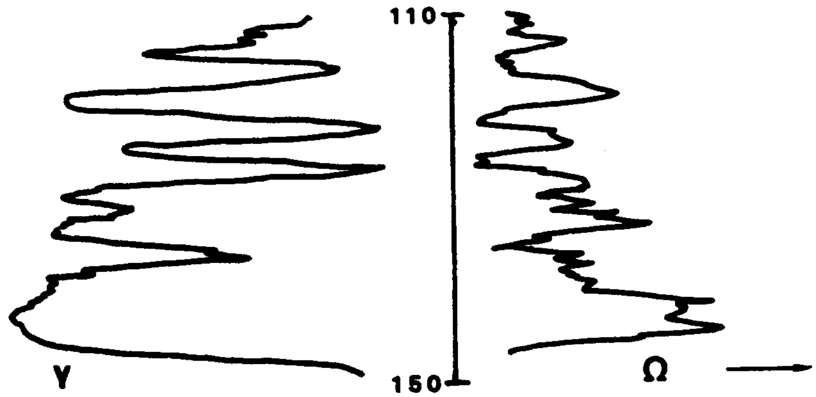
GAMMA

Probe #: 64G
Range: 500 (full)
Time Constant: 1
Chart Scale (CPS/in):
Logging Speed (Ft/min): 10

ELECTRIC

Resistivity Scale (Ohm/in): 40
Spontaneous Potential (mv/in):
Logging Speed (Ft/min): 10

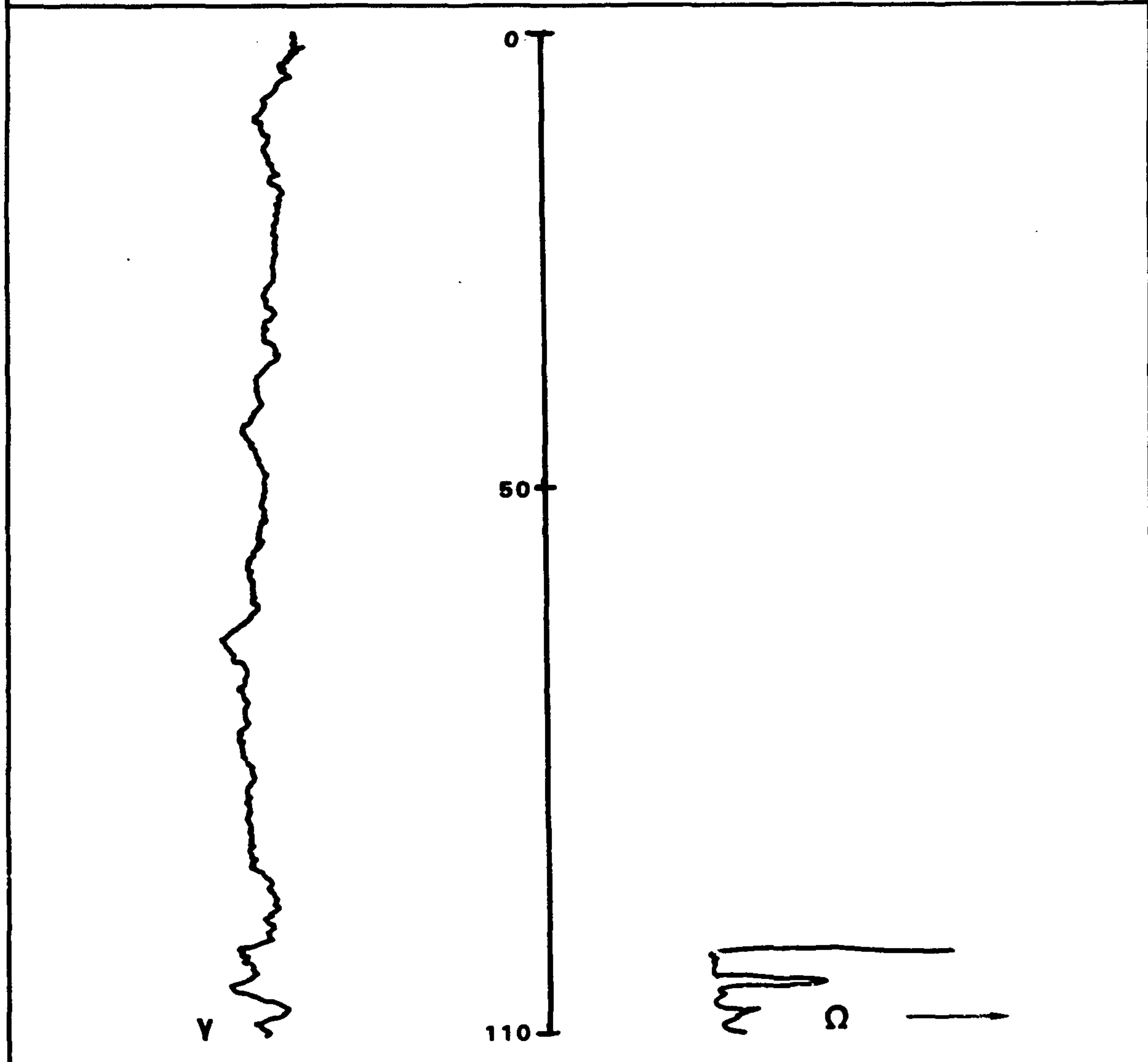


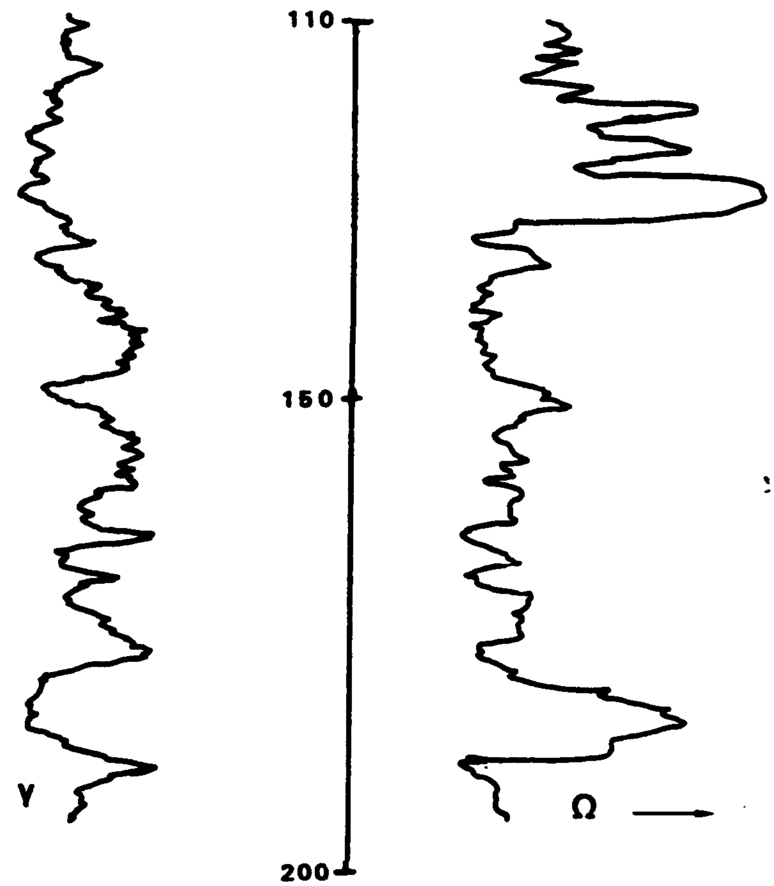


Boring 1123 Continued

Well Logging Co.: Western Well Logging, Inc.
Client: Army Corp of Engineers
Hole #: 1124 (SP-13) **Date:** 18 July, 1980
Location:
Depth Logged: 194' **Depth Drilled:**
Wire Line Operator: P. O'Brian **Unit/Instrument #:** L-4
Geologist/Witness: **Engineer:** Maj Zebell
Fluid Type: **Fluid Level:** **Time Since Circulation:**
Bit Size: **Cased Interval:**
Inside Casing Diameter: **Casing Thickness:**

GAMMA	ELECTRIC
Probe #: 64G	**Resistivity Scale (Ohm/in):** 40
Range: 500 (full)	**Spontaneous Potential (mv/in):**
Time Constant: 1	**Logging Speed (Ft/min):** 10
Chart Scale (CPS/in):	
Logging Speed (Ft/min): 10	





Boring 1124 Continued

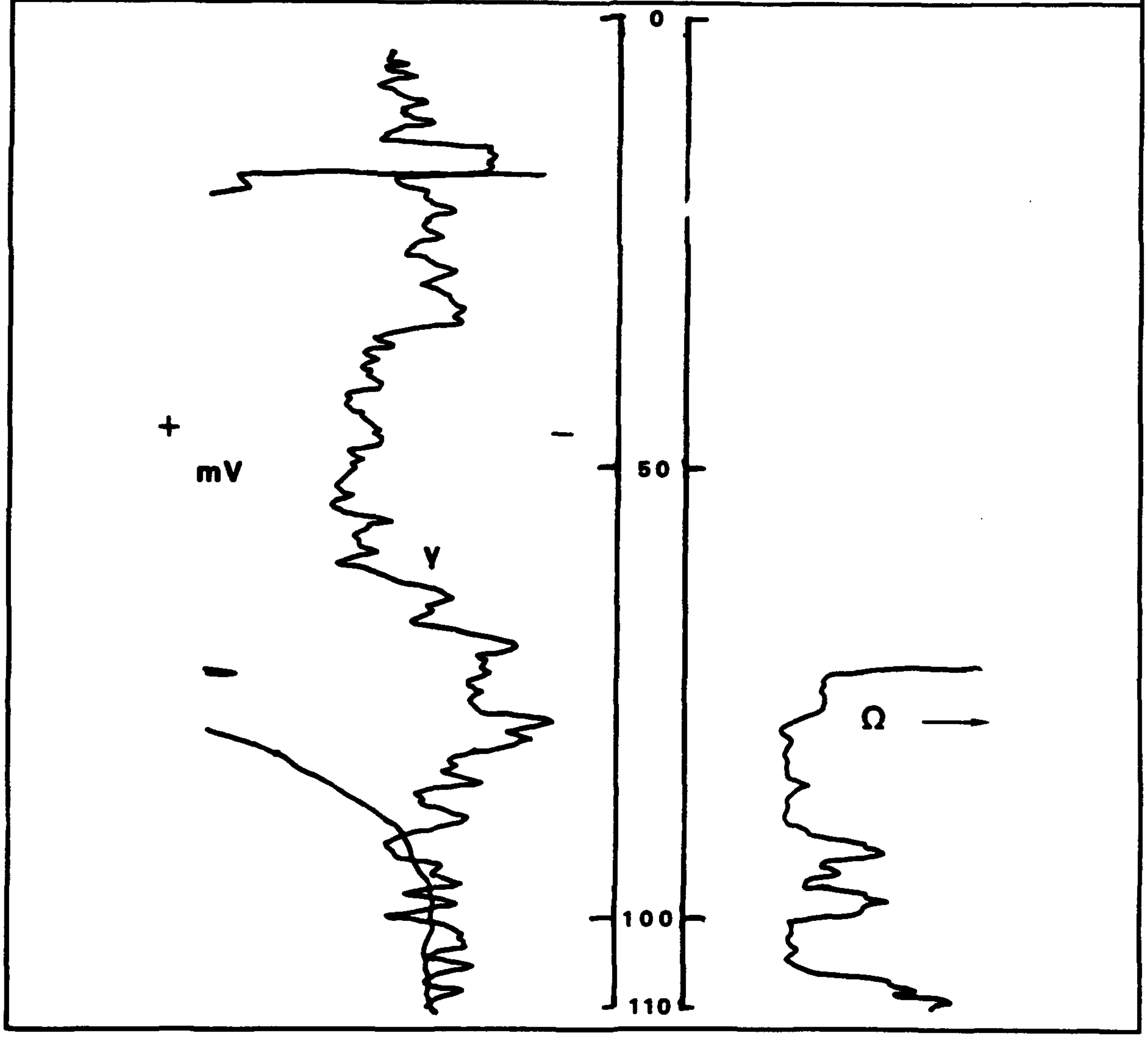
Well Logging Co.: Colorado Well Logging, Inc.
Client: U.S. Corps of Engineers
Hole #: 1143 (SP-16) Date: Nov. 21, 1980
Location: Rocky Mountain Arsenal (Fremont Co.) Colorado
Depth Logged: 165' Depth Drilled: 167'
Wire Line Operator: Luby Unit/Instrument #: 93
Geologist/Witness: Lawson Smith Engineer:
Fluid Type: Bentonite Fluid Level: 72' Time Since Circulation: 2 Hr
Bit Size: 4.5" Cased Interval: 0-69'
Inside Casing Diameter: Casing Thickness:

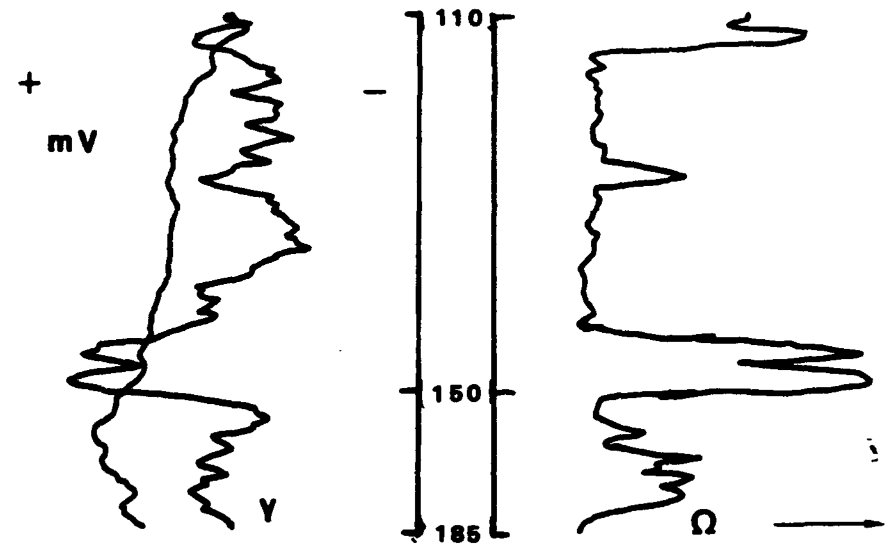
GAMMA

Probe #: 47
Range: 50 (full)
Time Constant: 1
Chart Scale (CPS/in): 10
Logging Speed (Ft/min): 15

ELECTRIC

Resistivity Scale (Ohm/in): 10
Spontaneous Potential (mv/in): 5
Logging Speed (Ft/min): 25

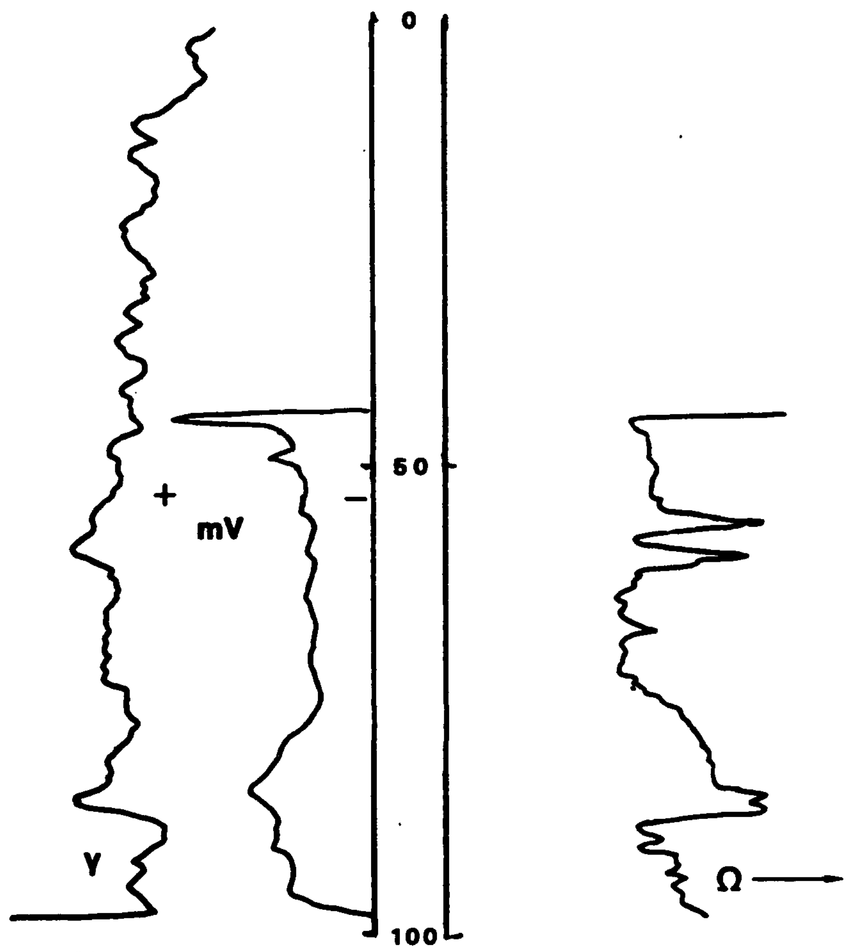




Boring 1143 Continued

Well Logging Co.: Colorado Well Logging, Inc.
Client: Corps of Engineers
Hole #: 1148 (SP-12) Date: 3 Dec., 1980
Location: Sec. 2, Adams Co., Colorado
Depth Logged: 98' Depth Drilled: 104.8'
Wire Line Operator: Mark Luby Unit/Instrument #: 2500
Geologist/Witness: Mr. Hunt Engineer:
Time Since
Fluid Type: Water Fluid Level: Circulation: 15 Hrs
Bit Size: 5 5/8" Cased Interval: to 44.5'
Inside Casing Diameter: Casing Thickness:

GAMMA	ELECTRIC
Probe #: 256	Resistivity Scale (Ohm/in): 20
Range: 50 (full)	Spontaneous Potential (mv/in): 5
Time Constant:	Logging Speed (Ft/min): 25
Chart Scale (CPS/in):	
Logging Speed (Ft/min): 10	



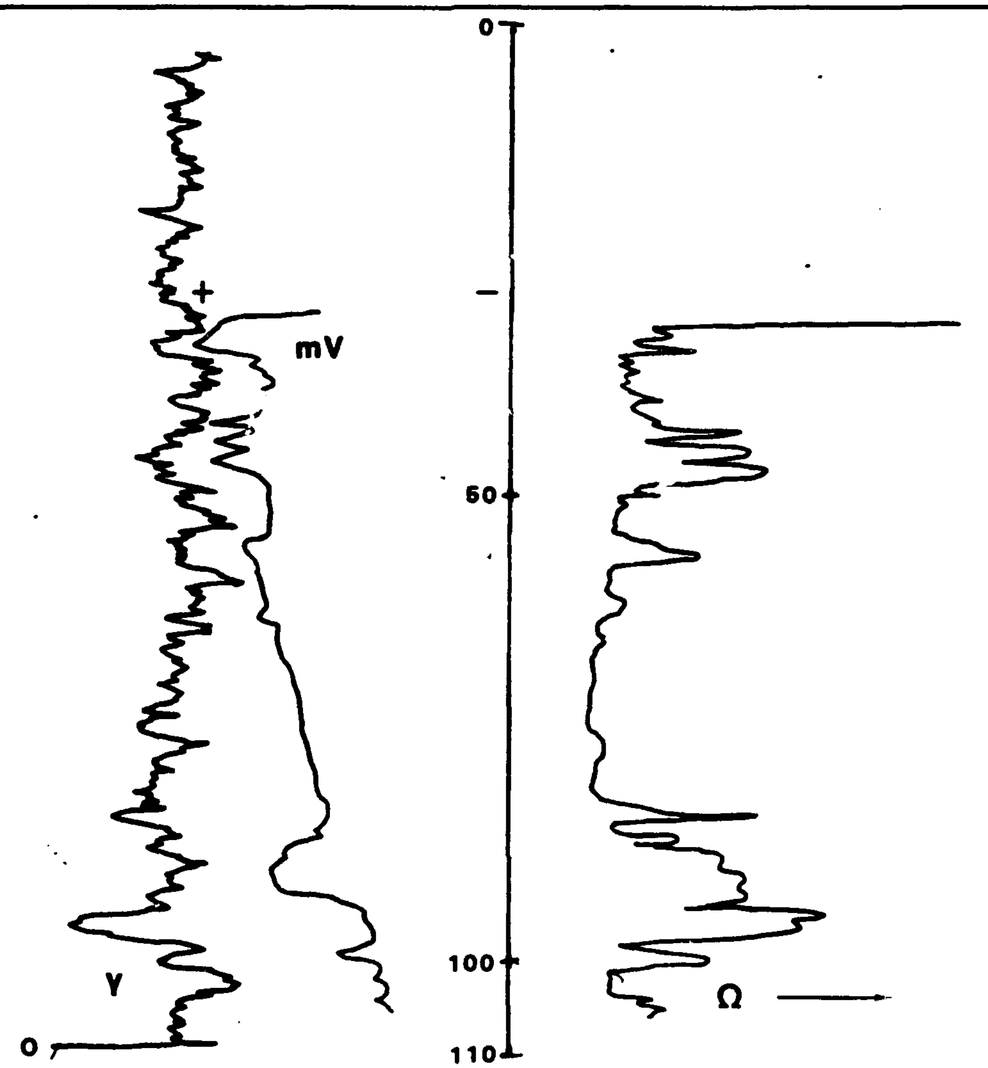
Well Logging Co.: Digilog, Inc.
Client: Corps of Engineers
Hole #: 1153 (SP-9) Date: 02/14/81
Location: Rocky Mountain Arsenal, Sec. 2, T2S, R67W
Depth Logged: 109' Depth Drilled: 109'
Wire Line Operator: R. Bouffard Unit/Instrument #: D-2
Geologist/Witness: Lt Col Zebell Engineer:
Fluid Type: Fluid Level: Time Since Circulation:
Bit Size: 5 5/8" Cased Interval: 0-31'
Inside Casing Diameter: 6" Casing Thickness:

GAMMA

Probe #: 1555
Range: 10/.5"
Time Constant: 2
Chart Scale (CPS/in): 10
Logging Speed (Ft/min): 10

ELECTRIC

Resistivity Scale (Ohm/in): 20
Spontaneous Potential (mv/in): 5
Logging Speed (Ft/min): 10



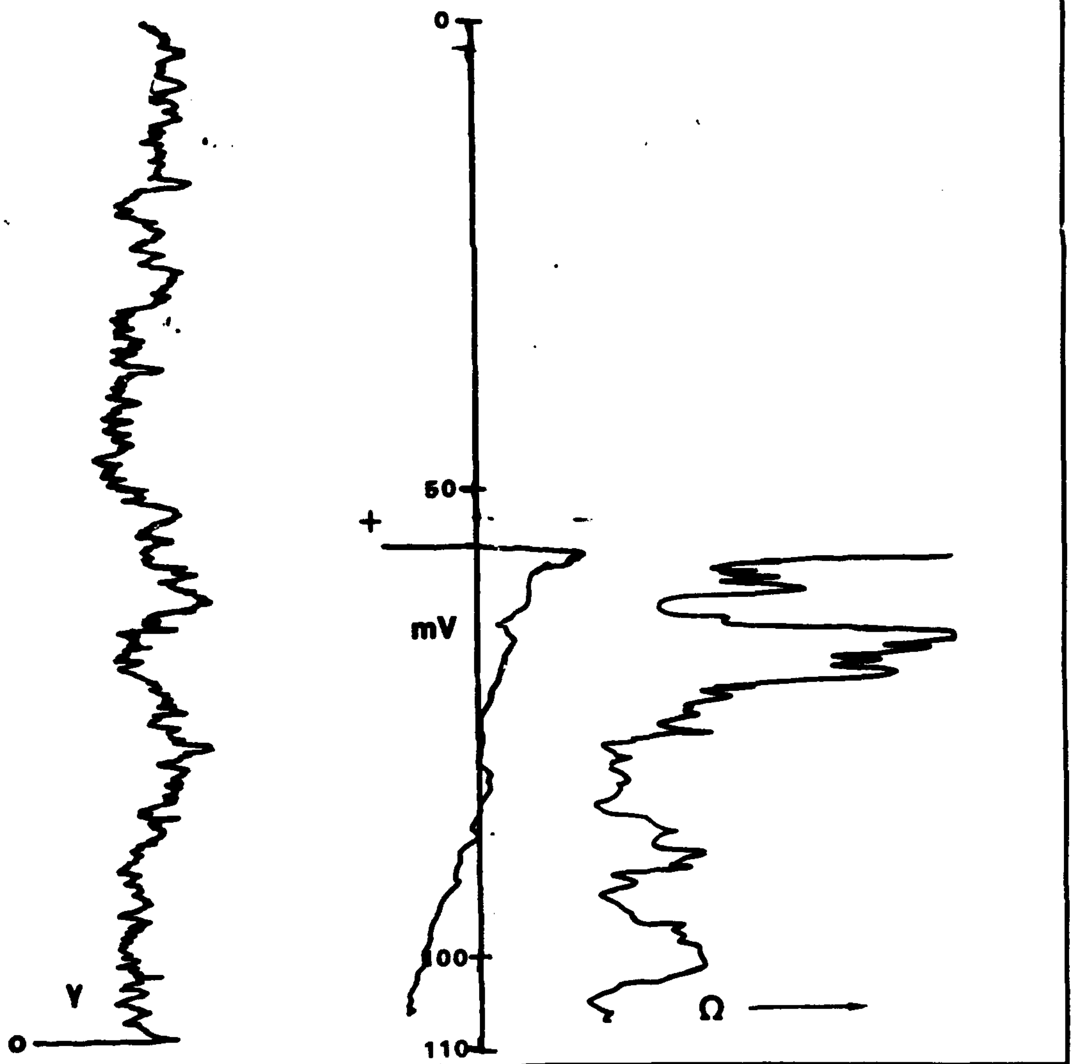
Well Logging Co.: Digilog, Inc.
Client: Corps of Engineers
Hole #: 1155 (SP-15) Date: 3-11-81
Location: Rocky Mtn. Arsenal, Adams Co., Colorado
Depth Logged: 109' Depth Drilled: 111'
Wire Line Operator: D. Delaney Unit/Instrument #: D-5
Geologist/Witness: R. Hunt Engineer:
Fluid Type: Fluid Level: Time Since Circulation:
Bit Size: 5 5/8" Cased Interval: 0-58'
Inside Casing Diameter: 6" Casing Thickness:

GAMMA

Probe #: 1555
Range: 10/.5"
Time Constant: 2
Chart Scale (CPS/in): 10
Logging Speed (Ft/min): 10

ELECTRIC

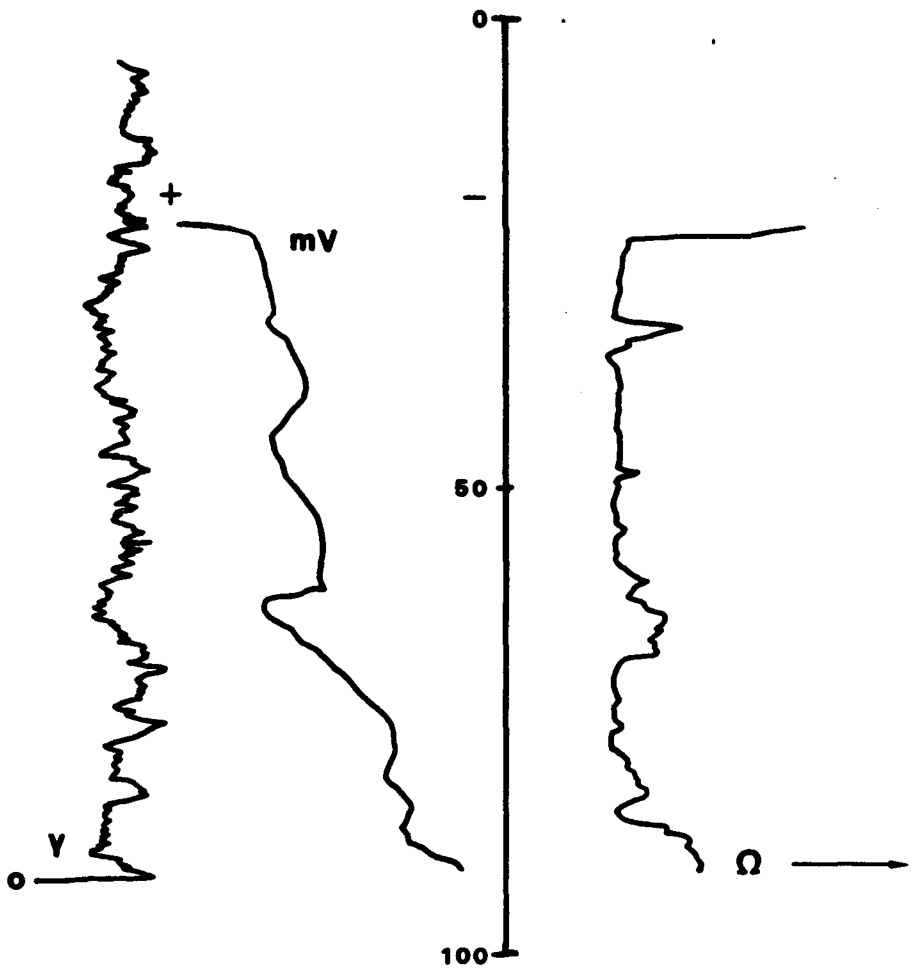
Resistivity Scale (Ohm/in): 10
Spontaneous Potential (mv/in): 5
Logging Speed (Ft/min): 10



Well Logging Co.: Digilog, Inc.
Client: Army Corp of Engineers
Hole #: 1160 (SP-2) **Date:** June 16, 1981
Location: R.M.A.
Depth Logged: 92' **Depth Drilled:** 92.8'
Wire Line Operator: C. Jones **Unit/Instrument #:** D-1
Geologist/Witness: Richard Hunt **Engineer:**
Fluid Type: **Fluid Level:** **Time Since Circulation:**
Bit Size: **Cased Interval:**
Inside Casing Diameter: **Casing Thickness:**

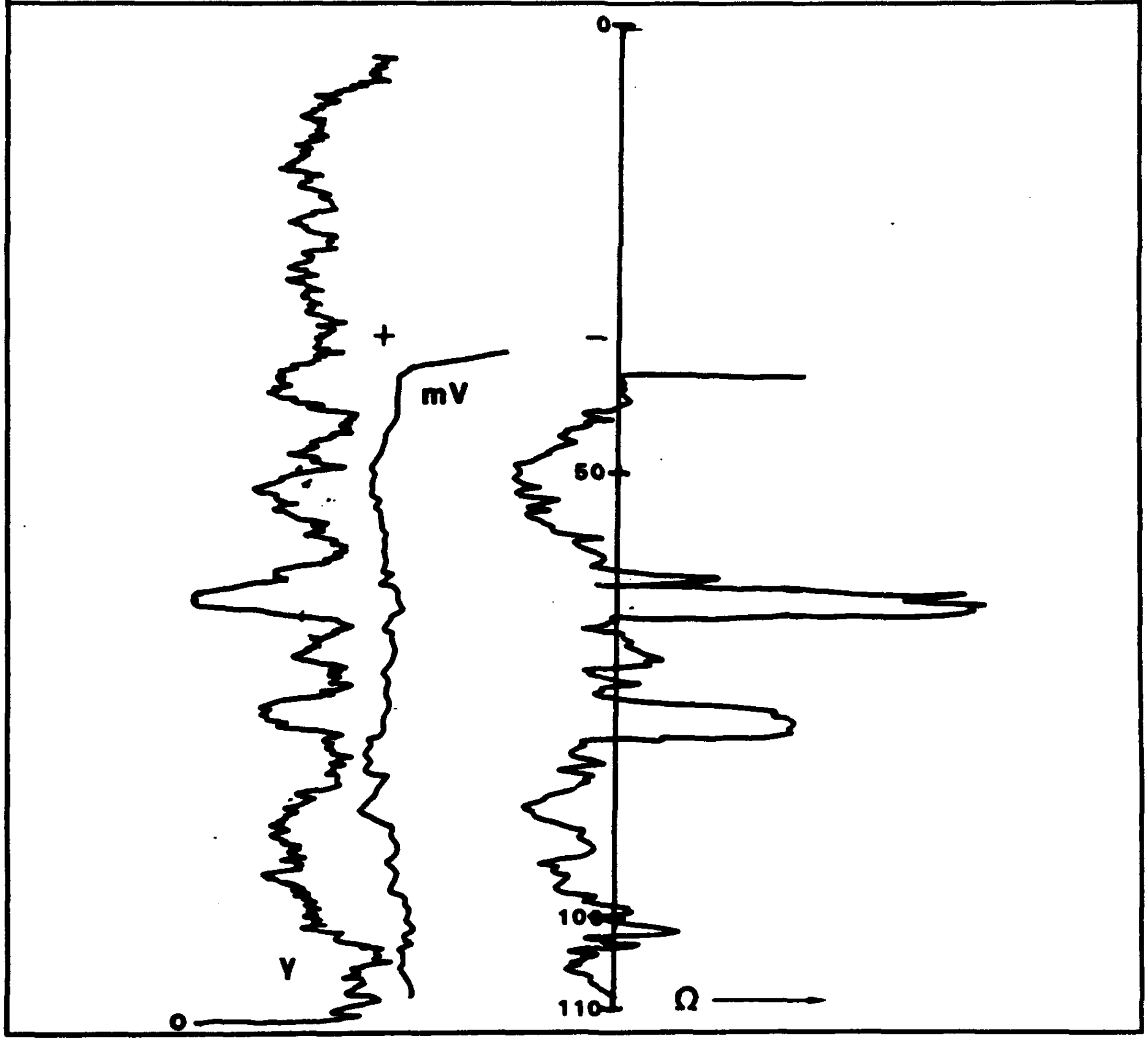
GAMMA
Probe #: 1555
Range: 20/.5"
Time Constant: 2
Chart Scale (CPS/in): 20
Logging Speed (Ft/min): 20

ELECTRIC
Resistivity Scale (Ohm/in): 20
Spontaneous Potential (mv/in): 10
Logging Speed (Ft/min): 20



Well Logging Co.: Digilog, Inc.
Client: Corps of Engineers
Hole #: 1185 (N-6) Date: 6/23/81
Location: RMA, Adams Co., Colorado
Depth Logged: 112' Depth Drilled: 117'
Wire Line Operator: C. Davis Unit/Instrument #: D-7
Geologist/Witness: Richard Hunt Engineer:
Fluid Type: Fluid Level: Time Since Circulation:
Bit Size: 5 5/8" Cased Interval: 0-39'
Inside Casing Diameter: Casing Thickness:

GAMMA	ELECTRIC
Probe #: 1482	Resistivity Scale (Ohm/in): 15
Range: 10/.5"	Spontaneous Potential (mv/in): 5
Time Constant: 2	Logging Speed (Ft/min): 15
Chart Scale (CPS/in): 10	
Logging Speed (Ft/min): 15	



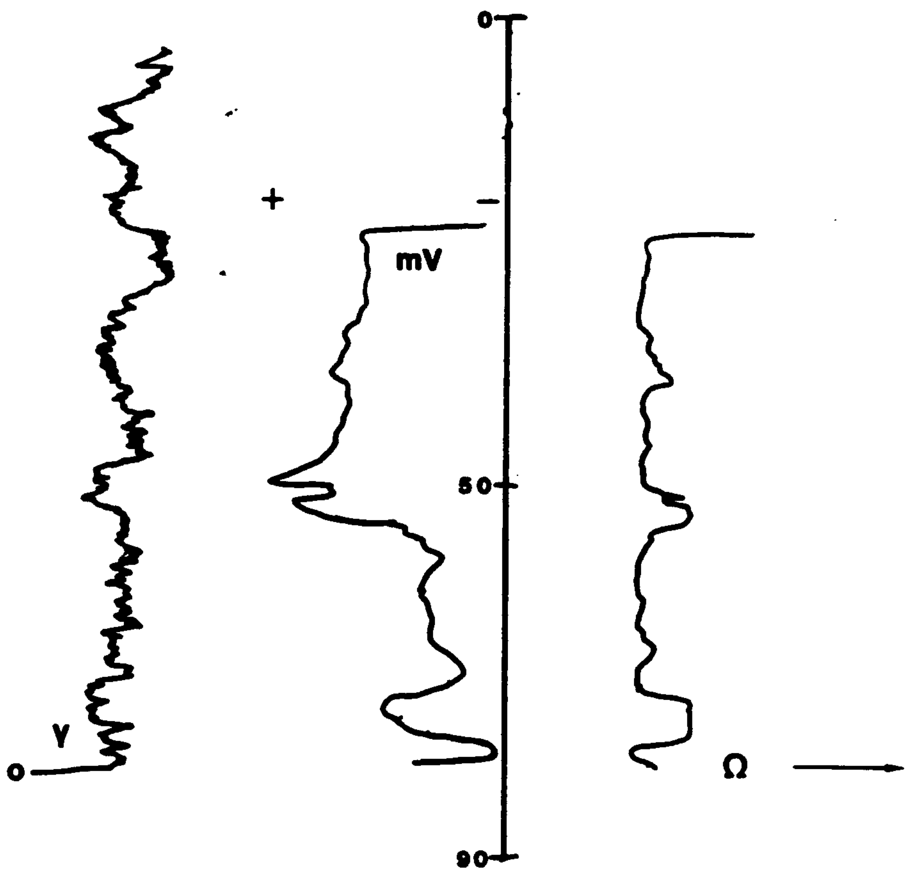
Well Logging Co.: Digilog, Inc.
Client: Army Corps Engineers
Hole #: 1188 (E-1) **Date:** June 16, 1981
Location: R.M.A.
Depth Logged: 81' **Depth Drilled:** 83'
Wire Line Operator: C. Jones **Unit/Instrument #:** D-1
Geologist/Witness: Richard Hunt **Engineer:**
Fluid Type: **Fluid Level:** **Time Since Circulation:**
Bit Size: **Cased Interval:**
Inside Casing Diameter: **Casing Thickness:**

GAMMA

Probe #: 1555
Range: 20/.5"
Time Constant: 2
Chart Scale (CPS/in): 20
Logging Speed (Ft/min): 20

ELECTRIC

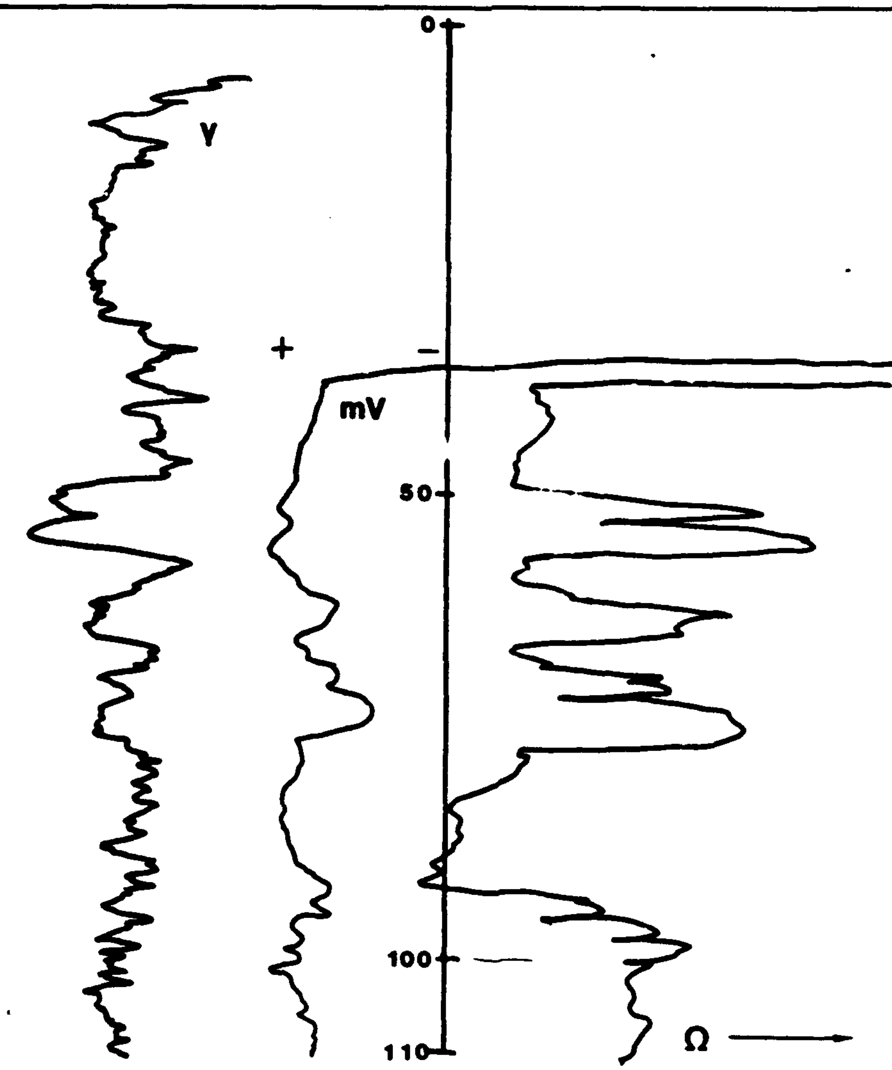
Resistivity Scale (Ohm/in): 20
Spontaneous Potential (mv/in): 10
Logging Speed (Ft/min):

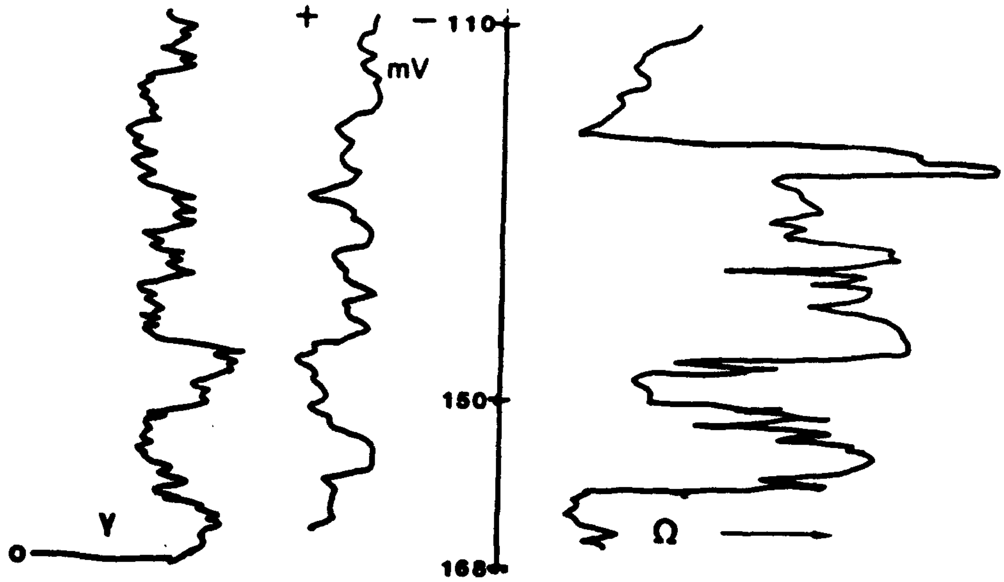


Well Logging Co.: Digilog, Inc.
Client: Army Corps of Engineers
Hole #: 1228 (AP-1) **Date:** 30 April, 1982
Location: Sec. 36, Colorado
Depth Logged: 168' **Depth Drilled:**
Wire Line Operator: Mike Hughes **Unit/Instrument #:** D-4
Geologist/Witness: Richard Hunt **Engineer:**
Fluid Type: **Fluid Level:** **Time Since Circulation:**
Bit Size: **Cased Interval:**
Inside Casing Diameter: **Casing Thickness:**

GAMMA
Probe #: 1555
Range: 10/.5"
Time Constant: 2
Chart Scale (CPS/in): 10
Logging Speed (Ft/min): 20

ELECTRIC
Resistivity Scale (Ohm/in): 10
Spontaneous Potential (mv/in): 10
Logging Speed (Ft/min): 20





Boring 1228 Continued

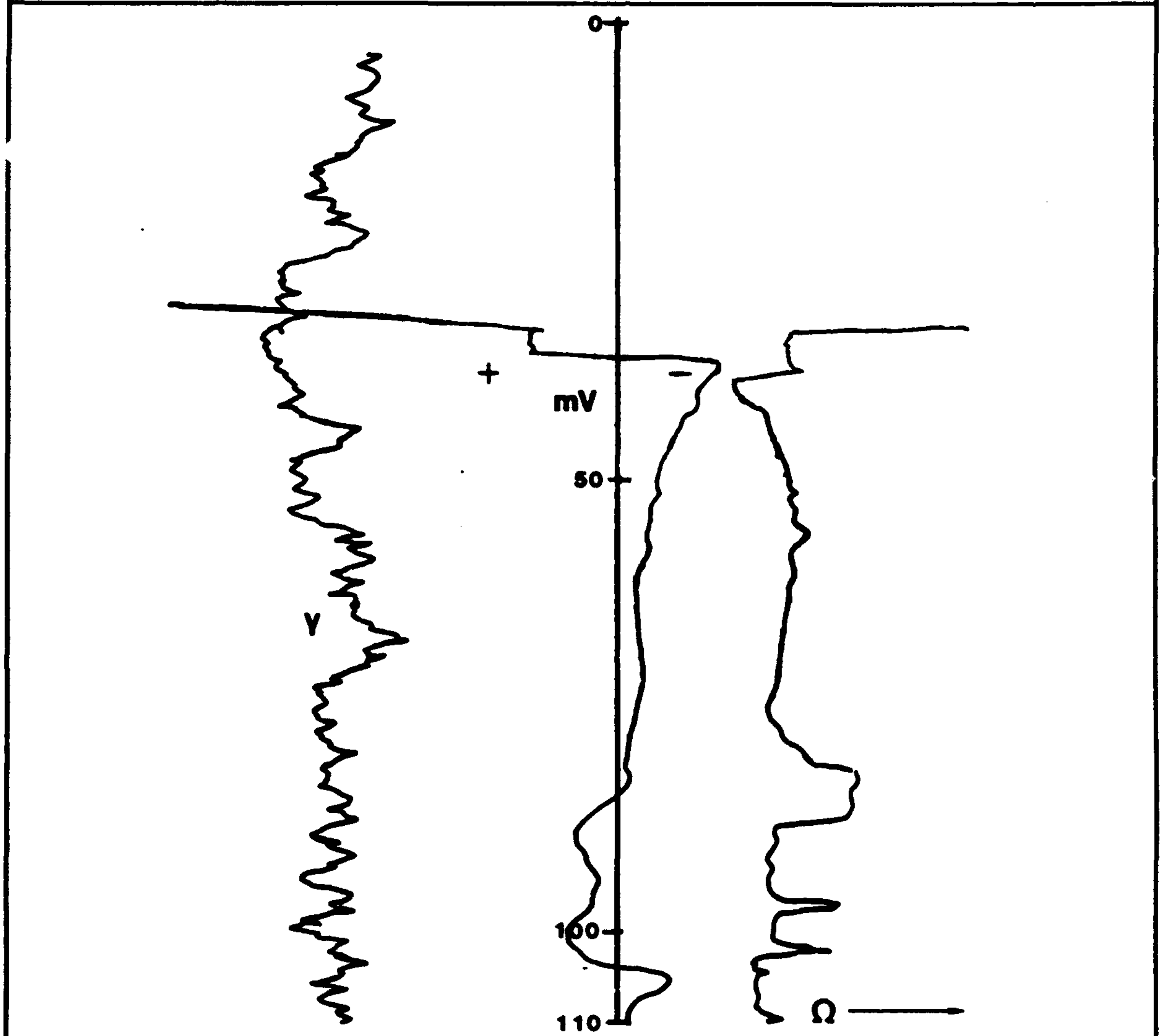
Well Logging Co.: Digilog, Inc.
Client: U.S. Army
Hole #: 1239 (AP-12) Date: 4/5/82
Location: Adams Co., Colorado
Depth Logged: 231' Depth Drilled:
Wire Line Operator: C. Jones Unit/Instrument #: D-1
Geologist/Witness: Richard Hunt Engineer:
Fluid Type: Fluid Level: Time Since Circulation:
Bit Size: Cased Interval:
Inside Casing Diameter: Casing Thickness:

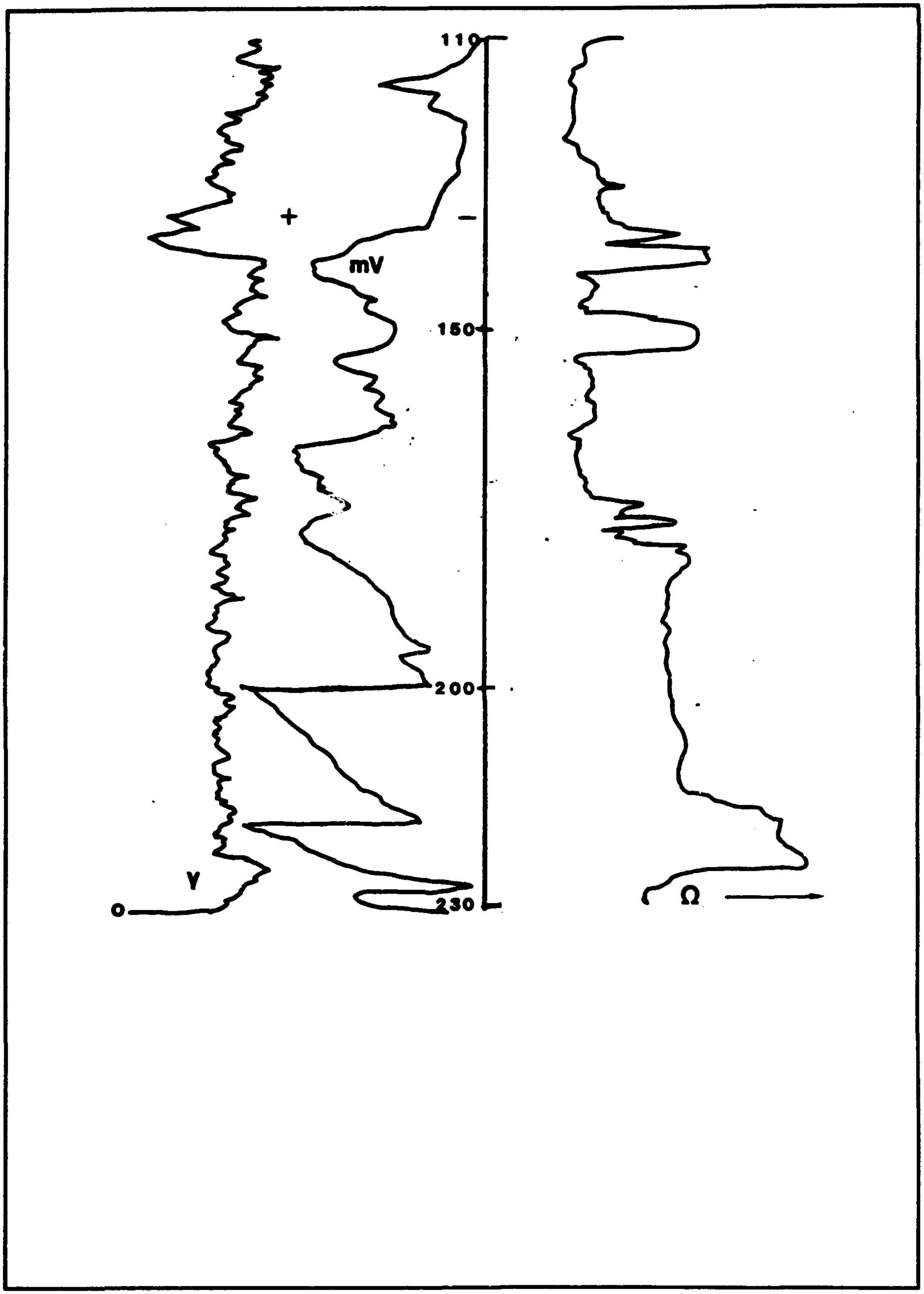
GAMMA

Probe #: 1489
Range: 10/.5"
Time Constant: 2
Chart Scale (CPS/in): 10
Logging Speed (Ft/min): 20

ELECTRIC

Resistivity Scale (Ohm/in): 20
Spontaneous Potential (mv/in): 10
Logging Speed (Ft/min): 20





Boring 1239 Continued

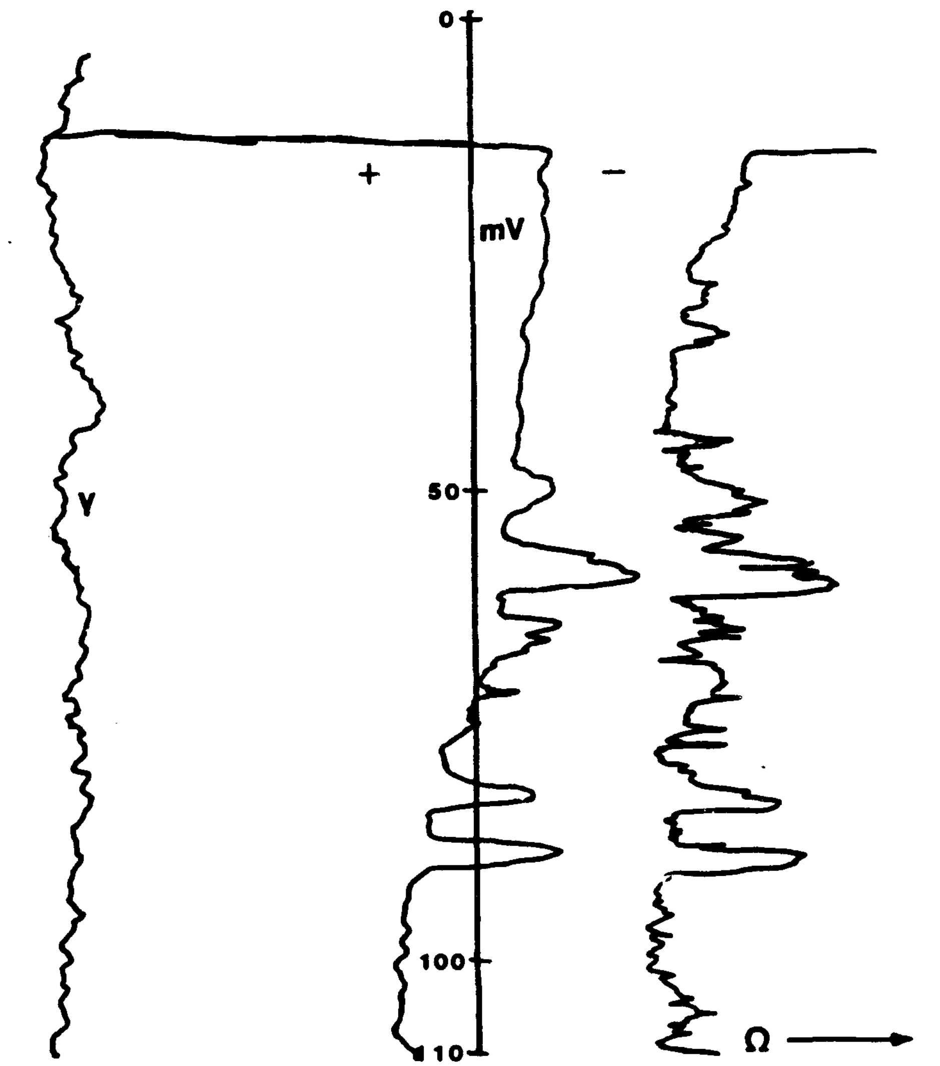
Well Logging Co.: Digilog, Inc.
Client: Corps of Engineers
Hole #: 1247 (AP-21) Date: 5-27-82
Location:
Depth Logged: 132' Depth Drilled: 132'
Wire Line Operator: Hohaus Unit/Instrument #: D-2
Geologist/Witness: Richard Hunt Engineer:
Fluid Type: Fluid Level: Time Since Circulation:
Bit Size: Cased Interval:
Inside Casing Diameter: Casing Thickness:

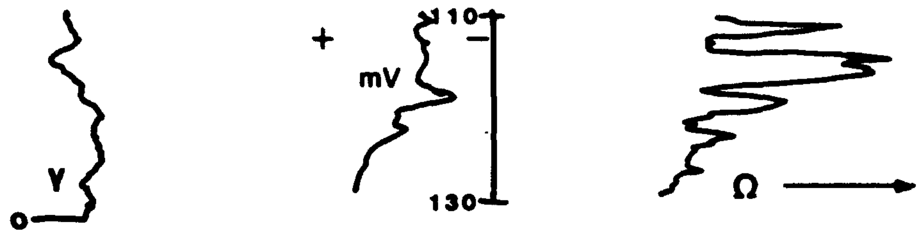
GAMMA

Probe #: 1430
Range: 10/.5"
Time Constant: 4
Chart Scale (CPS/in): 10
Logging Speed (Ft/min): 20

ELECTRIC

Resistivity Scale (Ohm/in): 20
Spontaneous Potential (mv/in): 20
Logging Speed (Ft/min): 20

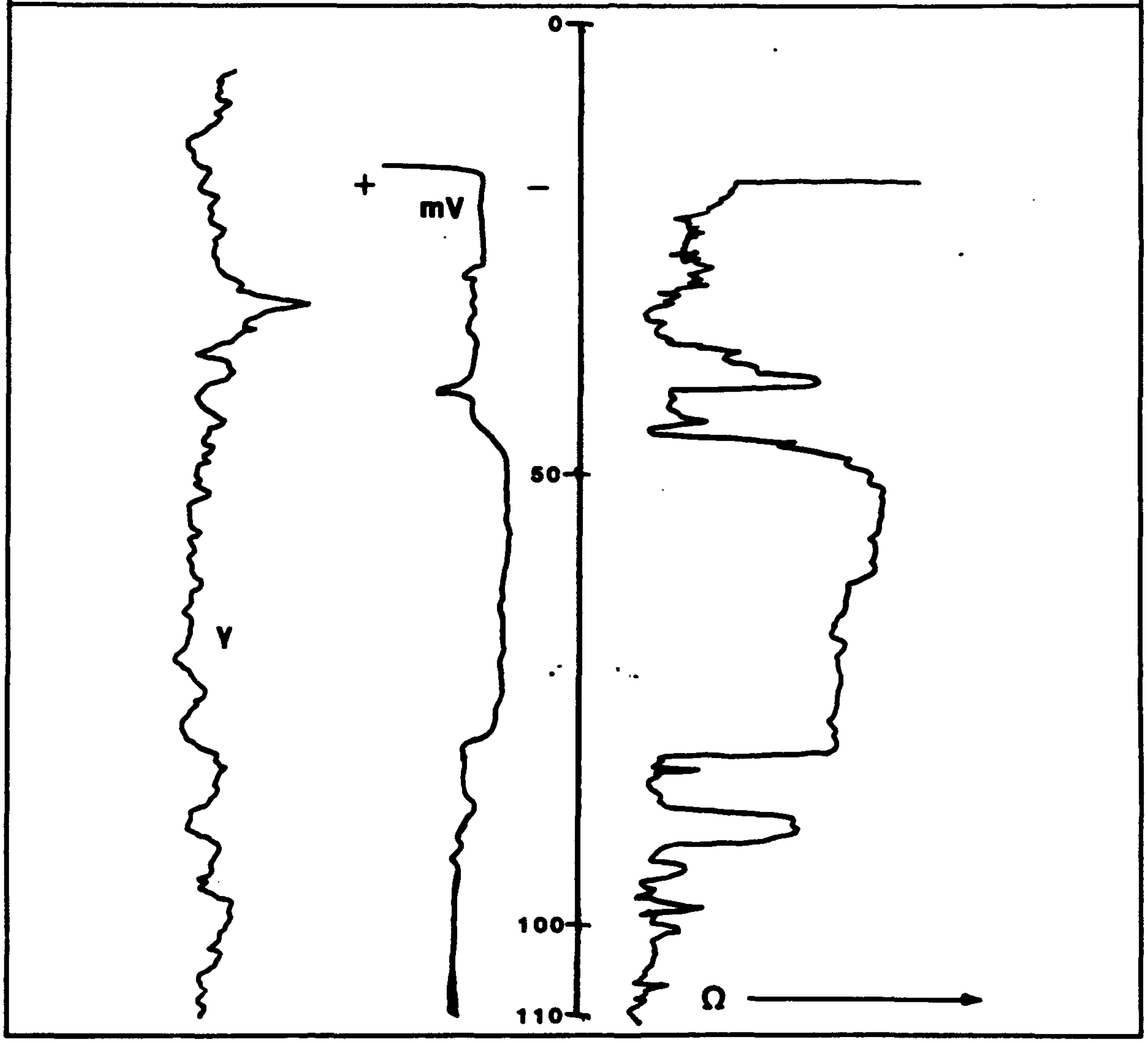


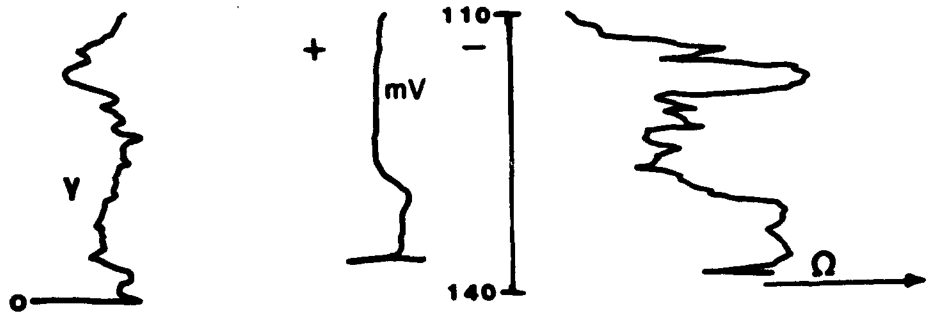


Boring 1247 Continued

Well Logging Co.: Digilog, Inc.
Client: U.S. Army Engineers
Hole #: 1251 (AP-25) **Date:** 5-6-82
Location: Adams Co., Colorado
Depth Logged: 141' **Depth Drilled:** 143'
Wire Line Operator: C. Jones **Unit/Instrument #:** D-4
Geologist/Witness: Richard Hunt **Engineer:**
Fluid Type: **Fluid Level:** **Time Since Circulation:**
Bit Size: **Cased Interval:**
Inside Casing Diameter: **Casing Thickness:**

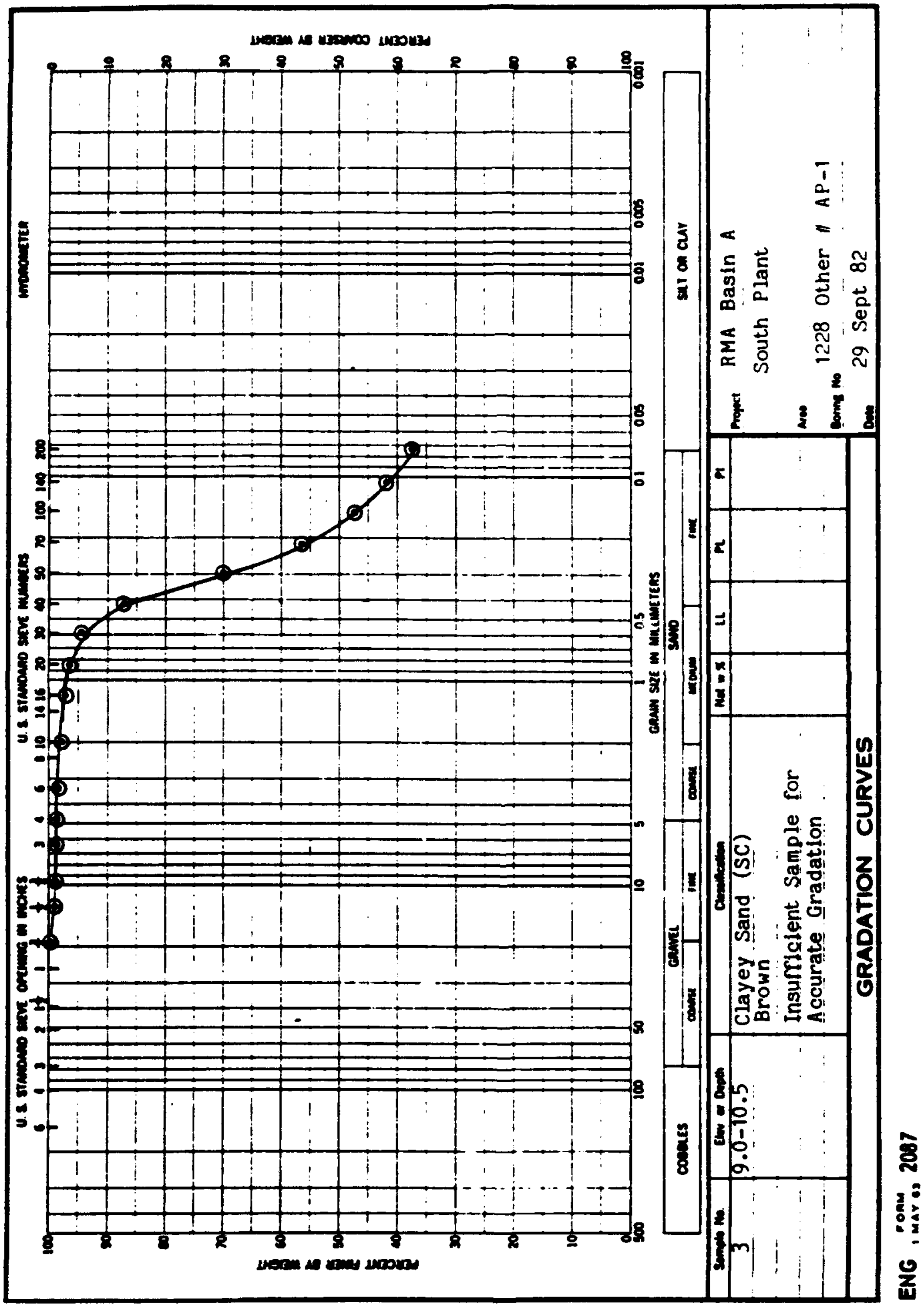
GAMMA	ELECTRIC
Probe #: 1489	**Resistivity Scale (Ohm/in):** 40
Range: 20/.5"	**Spontaneous Potential (mv/in):** 10
Time Constant: 4	**Logging Speed (Ft/min):** 20
Chart Scale (CPS/in): 20	
Logging Speed (Ft/min): 20	

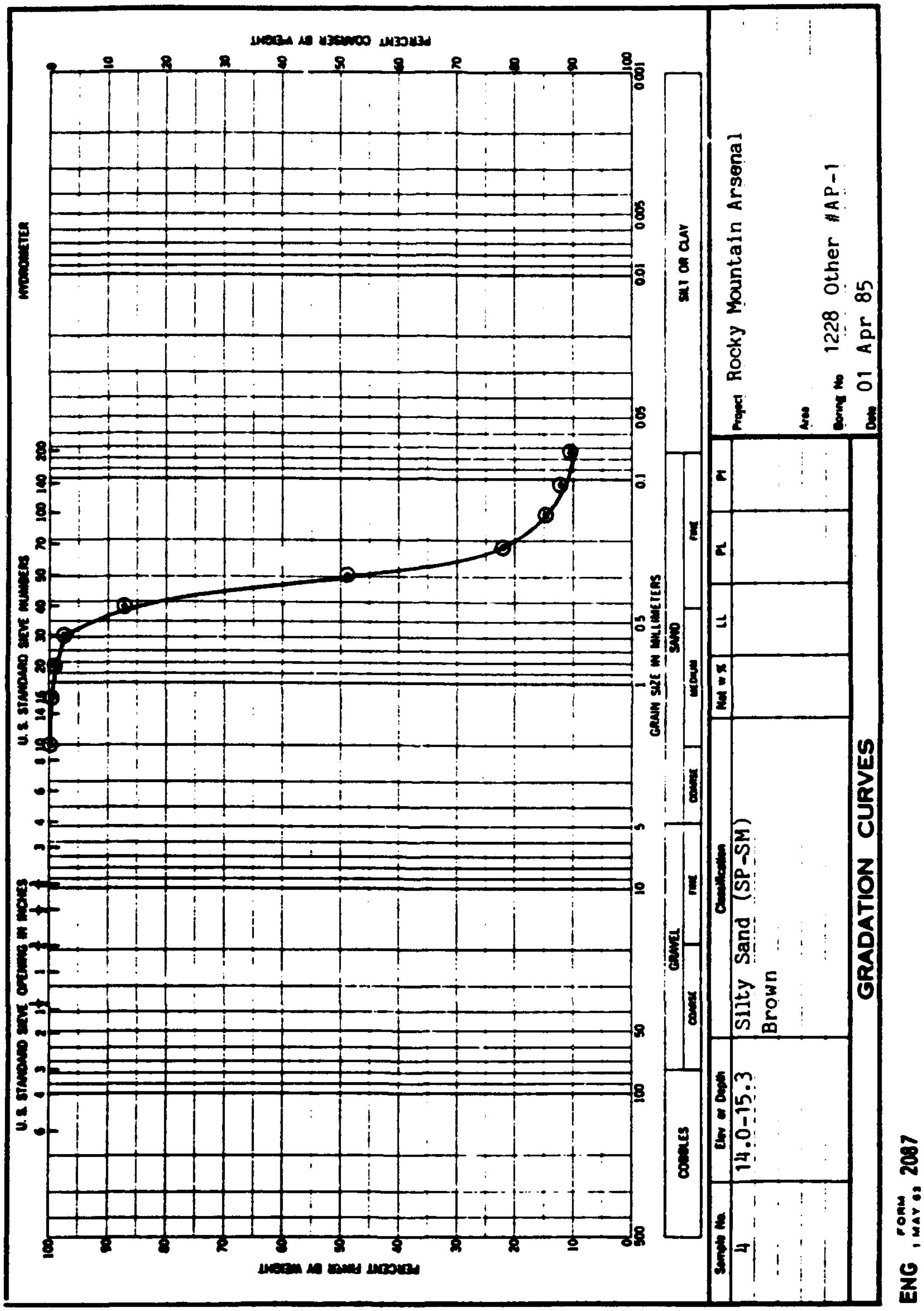


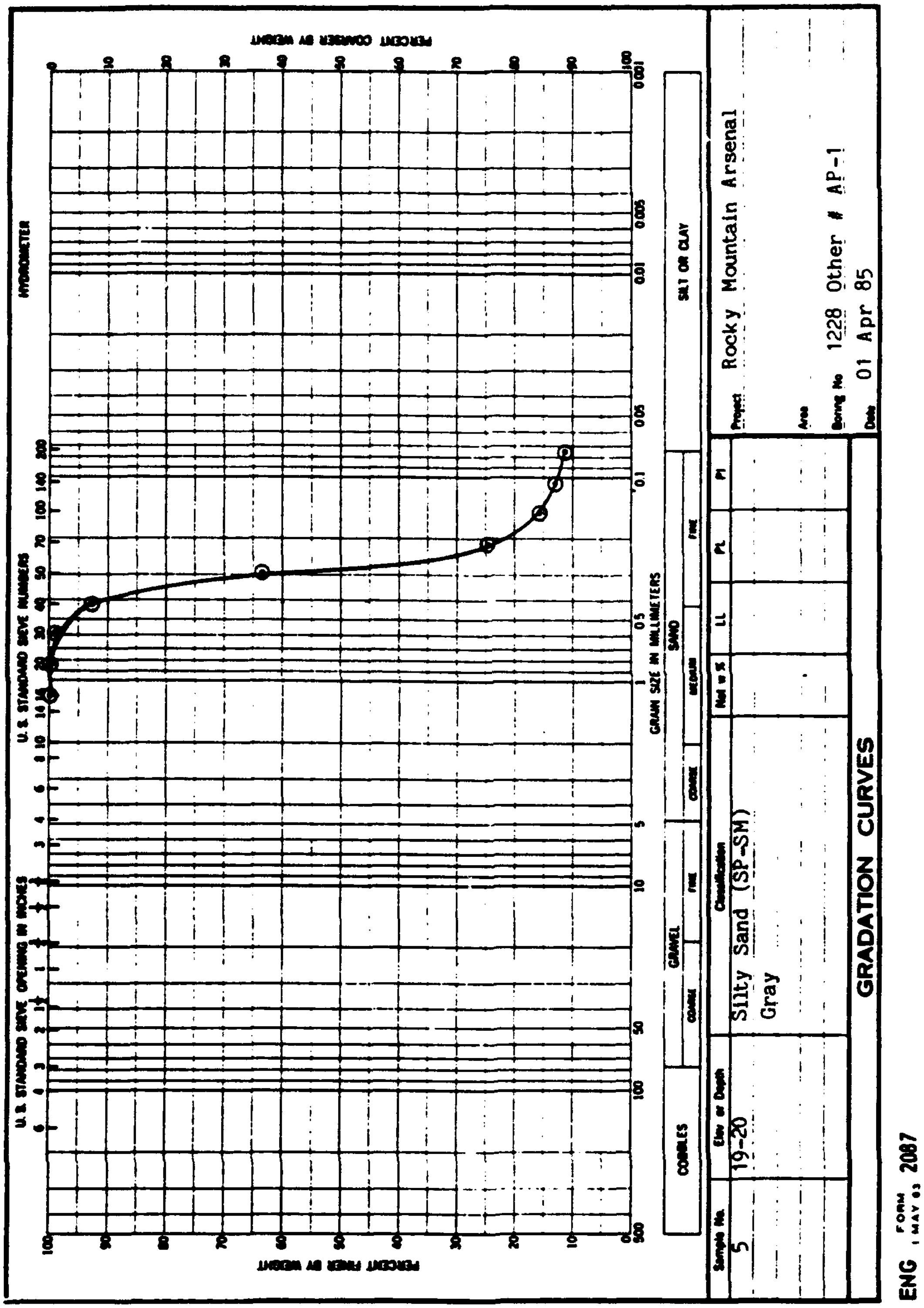


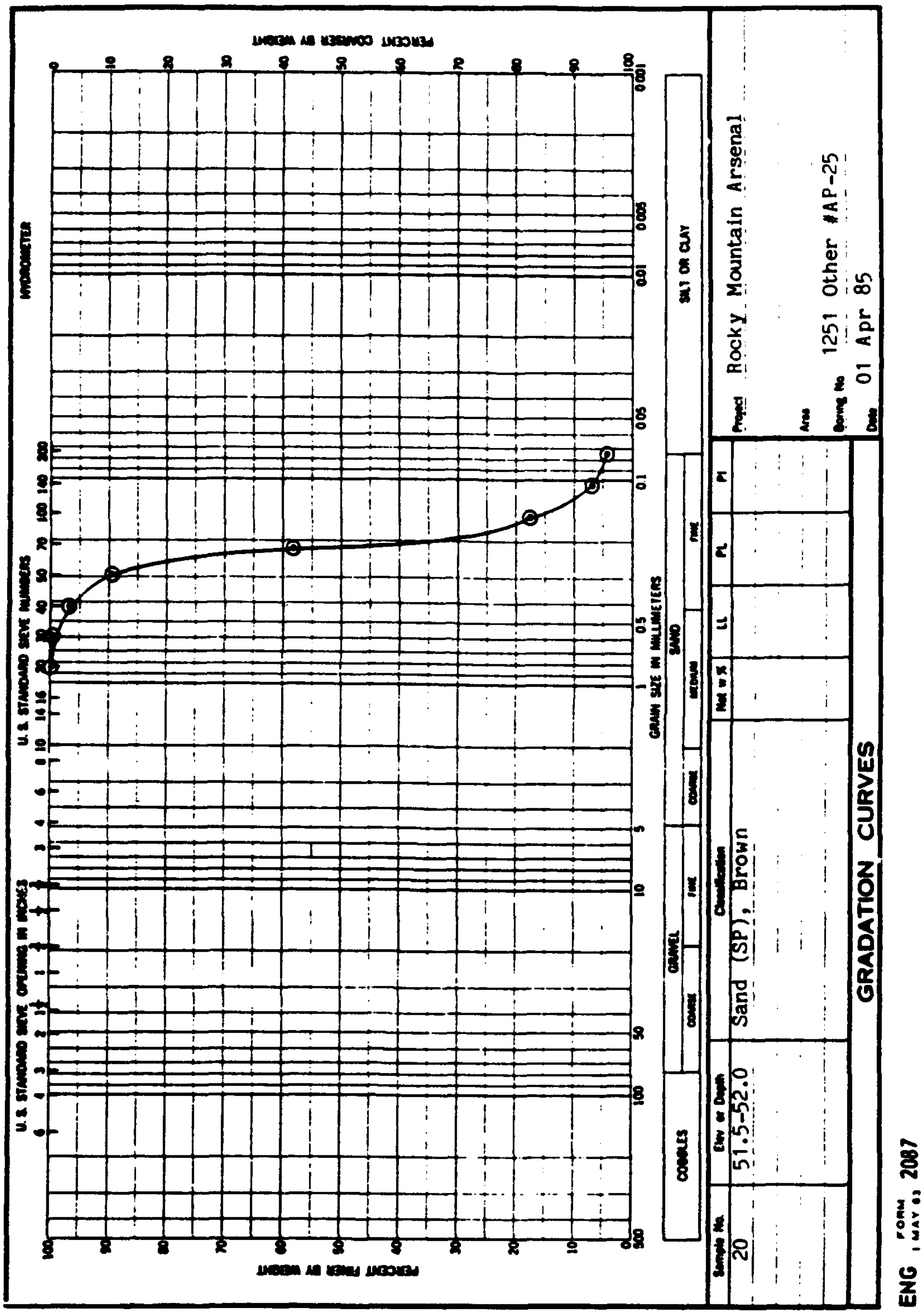
Boring 1251 Continued

Appendix J
Gradation Curves

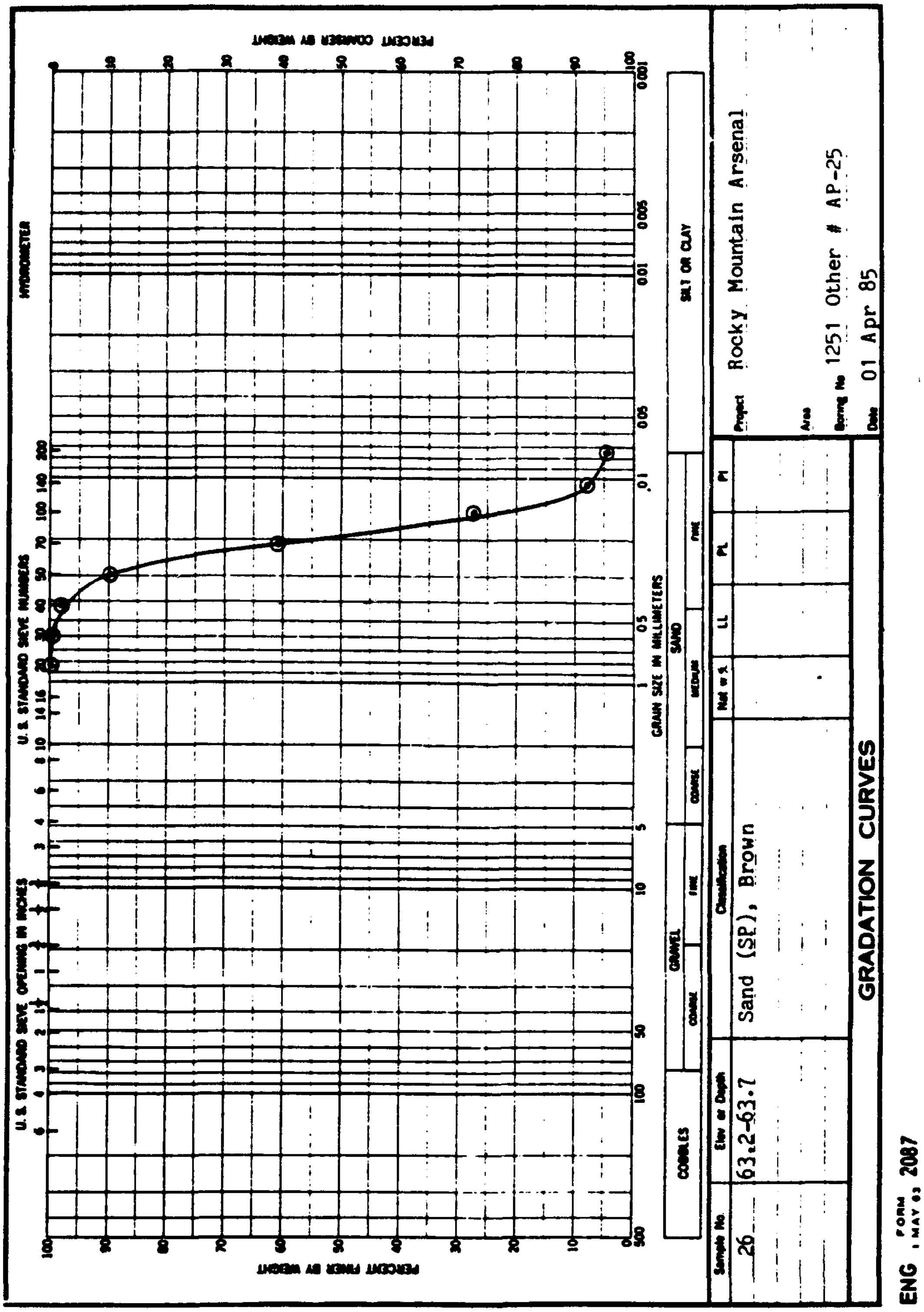

U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
Sample No.
3
Elev or Depth
9.0-10.5
Classification
Clayey Sand (SC)
Brown
Insufficient Sample for
Accurate Gradation
Nat w %
LL
PL
PI
Project
RMA Basin A
South Plant
Area
Boring No
1228 Other # AP-1
Date
29 Sept 82
GRADATION CURVES
ENG FORM 1 MAY 63 2087

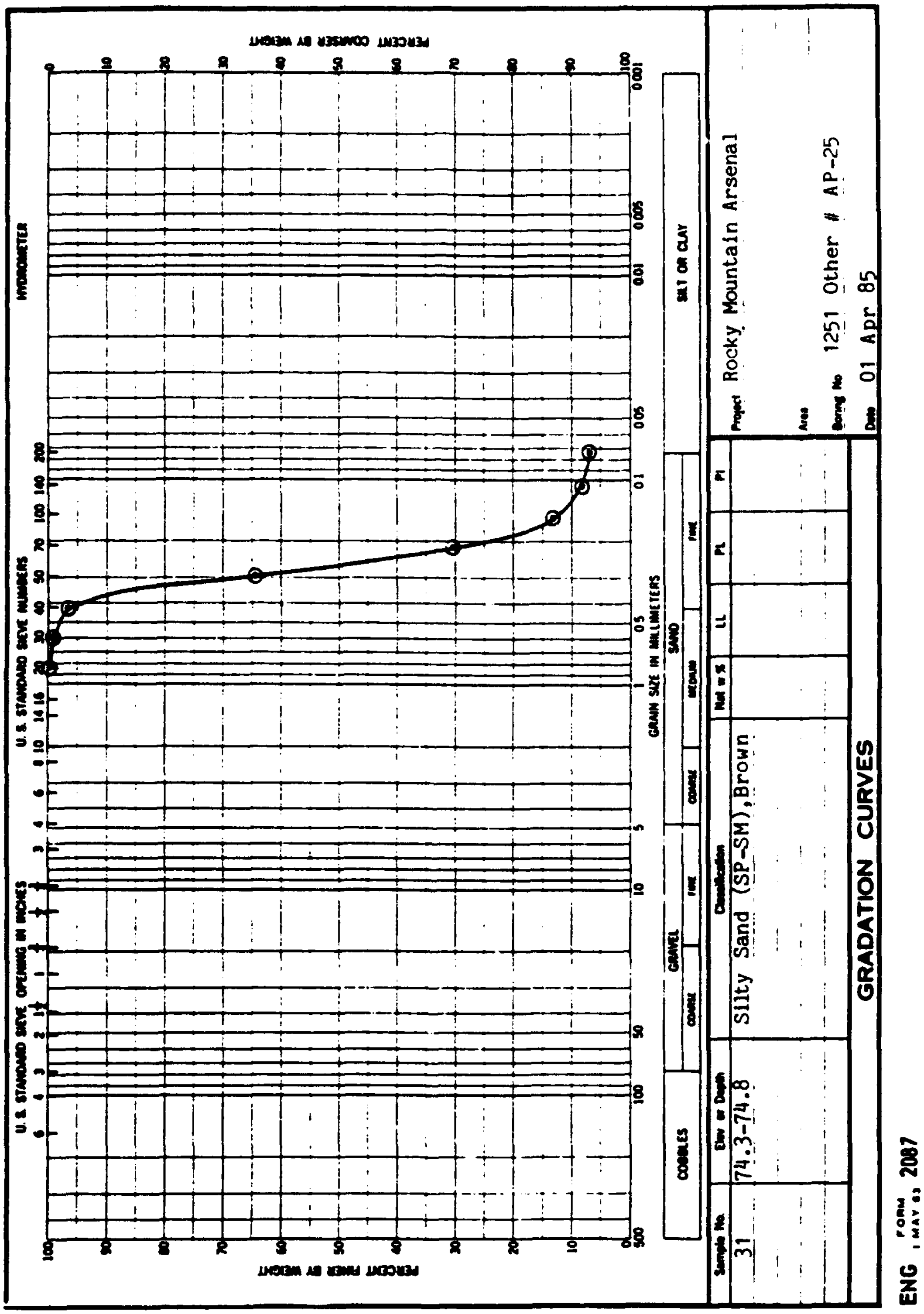

U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
Sample No.
Elev or Depth
Classification
Nat w %
LL
PL
PI
4
14.0-15.3
Silty Sand (SP-SM)
Brown
Project Rocky Mountain Arsenal
Area
Boring No 1228 Other #AP-1
Date 01 Apr 85
GRADATION CURVES
ENG FORM 1 MAY 63 2087

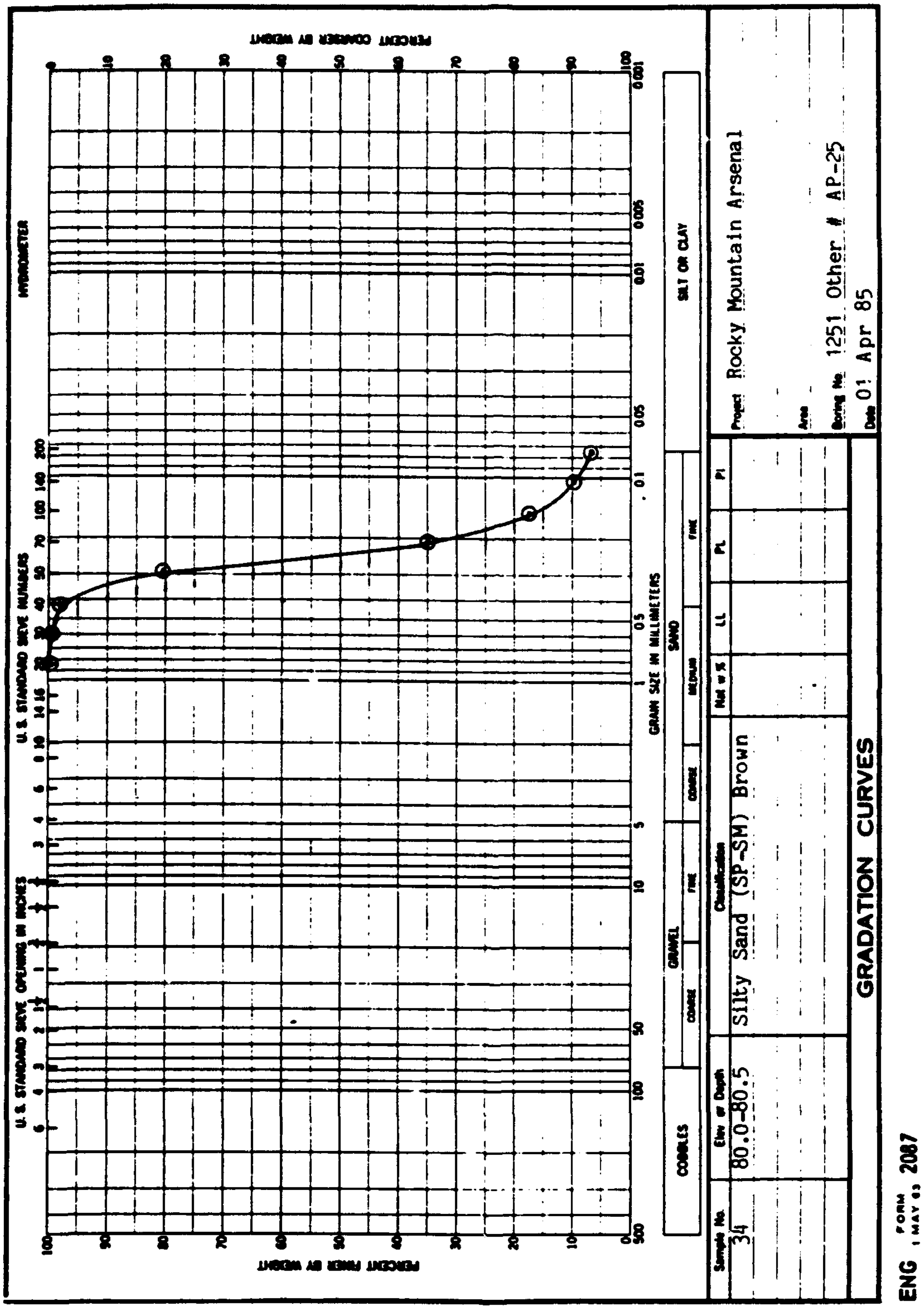

GRADATION CURVES
U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
SAND
SILT OR CLAY
Sample No.
5
Elev or Depth
19-20
Classification
Silty Sand (SP-SM)
Gray
Nat w %
LL
PL
PI
Project Rocky Mountain Arsenal
Area
Boring No 1228 Other # AP-1
Date 01 Apr 85
ENG FORM 2087
1 MAY 63



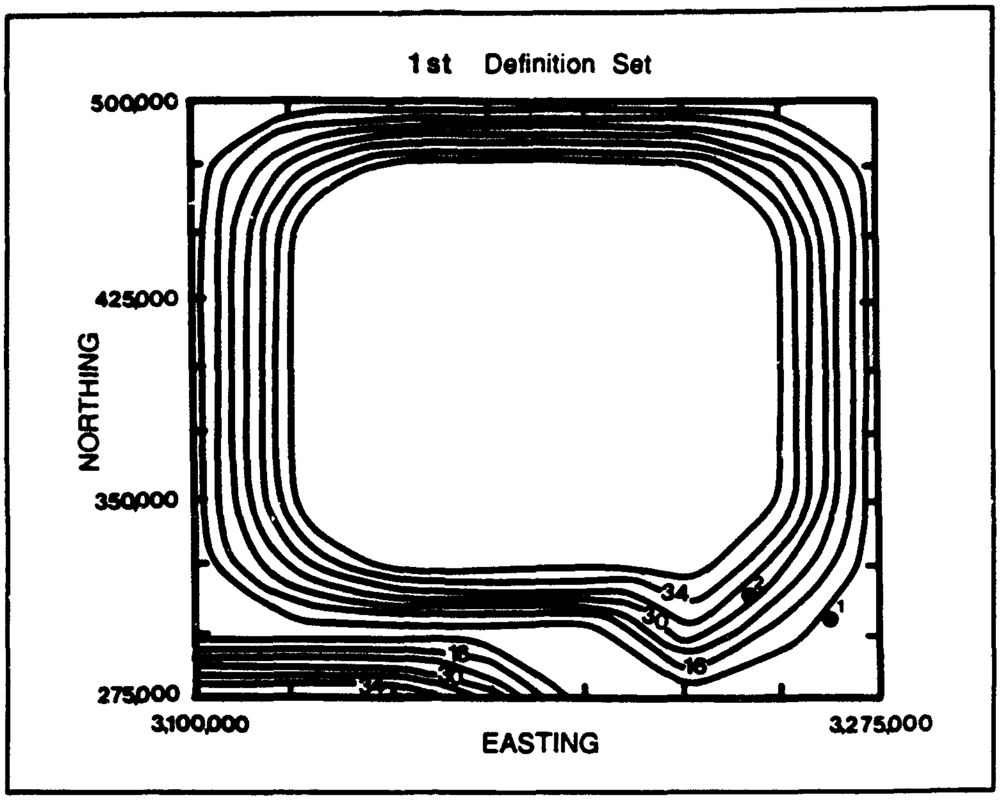
GRADATION CURVES
Project Rocky Mountain Arsenal
Boring No 1251 Other #AP-25
Date 01 Apr 85
Sample No. 20
Elev or Depth 51.5-52.0
Classification Sand (SP), Brown
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
COBBLES
GRAVEL
SAND
SILT OR CLAY
ENG FORM 2087


U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
Sample No.
Elev or Depth
Classification
Nat w %
LL
PL
PI
26
63.2-63.7
Sand (SP), Brown
Project
Rocky Mountain Arsenal
Area
Boring No
1251 Other # AP-25
Date
01 Apr 85
GRADATION CURVES
ENG FORM 1 MAY 63 2087


U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT FINER BY WEIGHT
PERCENT COARSER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
Sample No.
31
Elev or Depth
74.3-74.8
Classification
Silty Sand (SP-SM), Brown
Nat w %
LL
PL
PI
Project Rocky Mountain Arsenal
Area
Boring No 1251 Other # AP-25
Date 01 Apr 85
GRADATION CURVES
ENG FORM 1 MAY 63 2087


U. S. STANDARD SIEVE OPENING IN INCHES
U. S. STANDARD SIEVE NUMBERS
HYDROMETER
PERCENT COARSER BY WEIGHT
PERCENT FINER BY WEIGHT
GRAIN SIZE IN MILLIMETERS
COBBLES
GRAVEL
COARSE
FINE
SAND
COARSE
MEDIUM
FINE
SILT OR CLAY
Sample No.
Elev or Depth
Classification
Nat w %
LL
PL
PI
34
80.0-80.5
Silty Sand (SP-SM) Brown
Project Rocky Mountain Arsenal
Area
Boring No. 1251 Other # AP-25
Date 01 Apr 85
GRADATION CURVES
ENG FORM 1 MAY 63 2087

Appendix K
Standard Deviation Contours with Data Point Locations



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275,000
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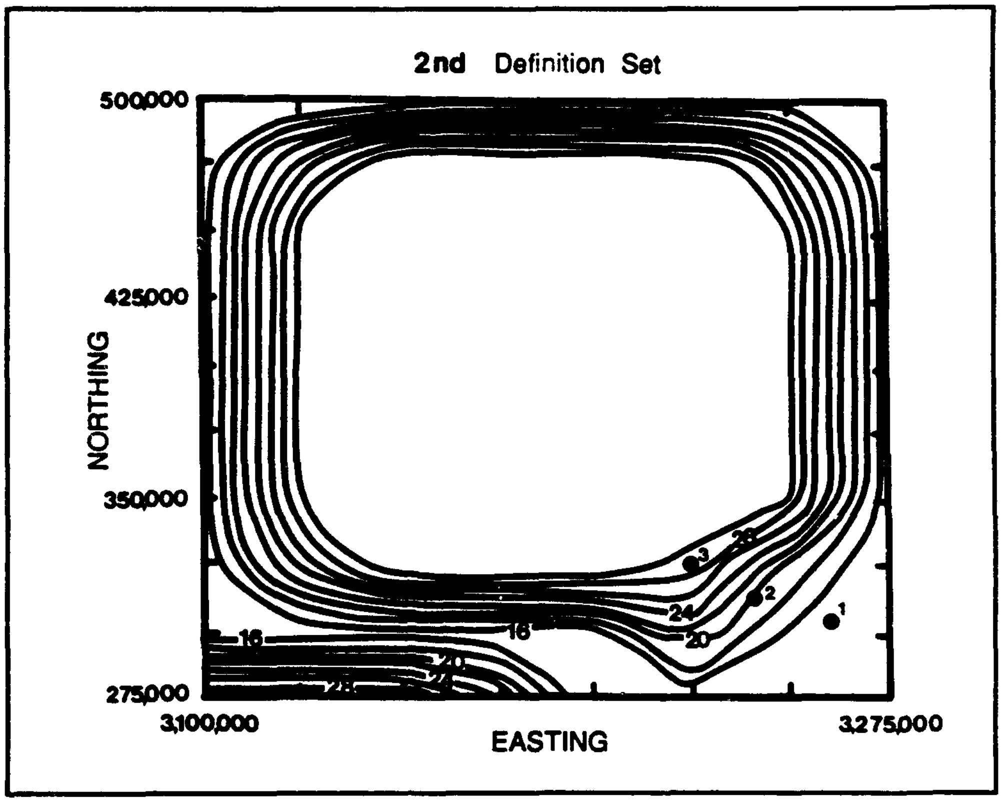
3,100,000
3,275,000
EASTING
34
30
16
32
1
2



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24
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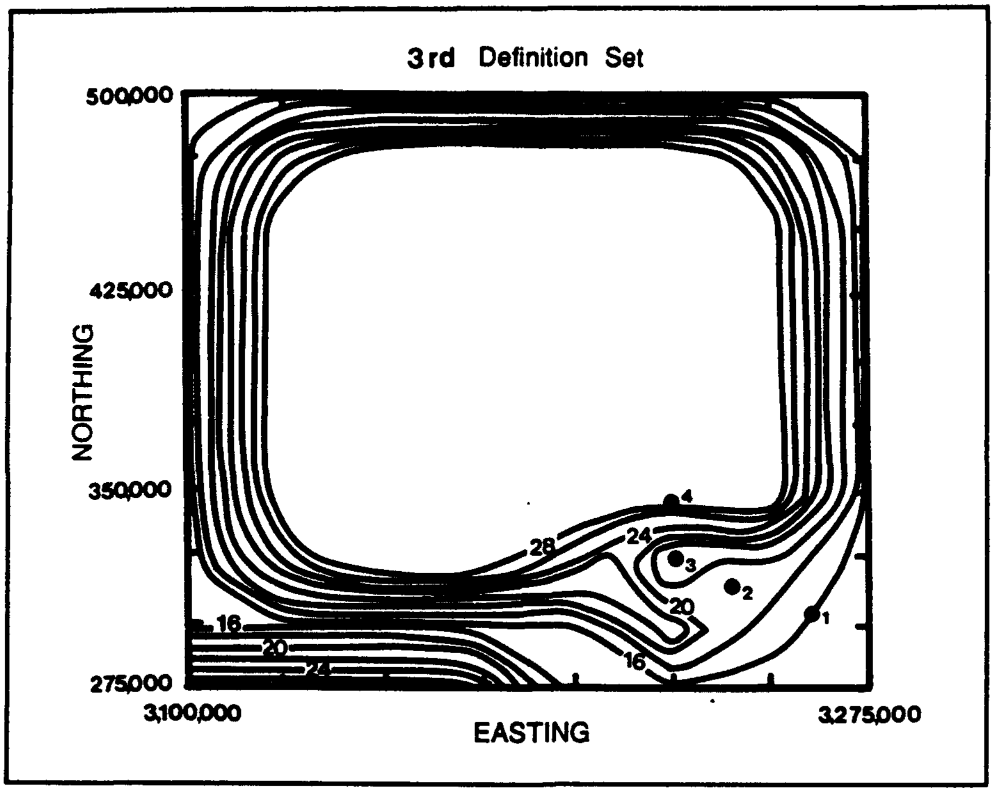

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EASTING
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24
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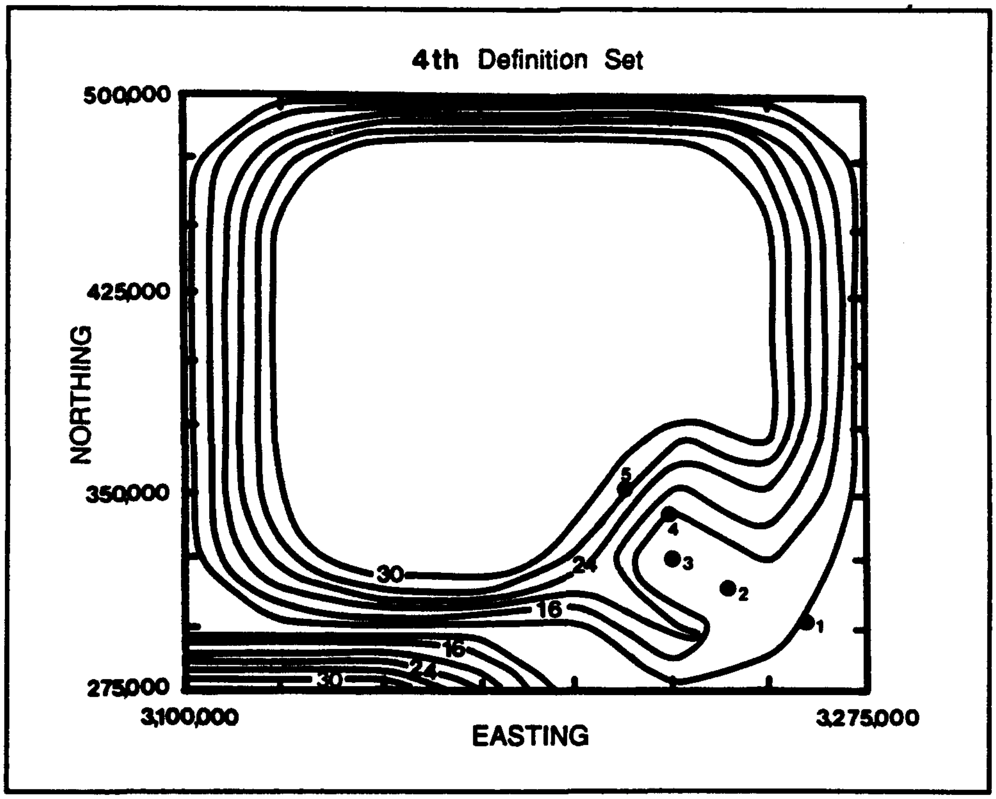
16
16
20
24
1
2
3
4



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275,000
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EASTING
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24
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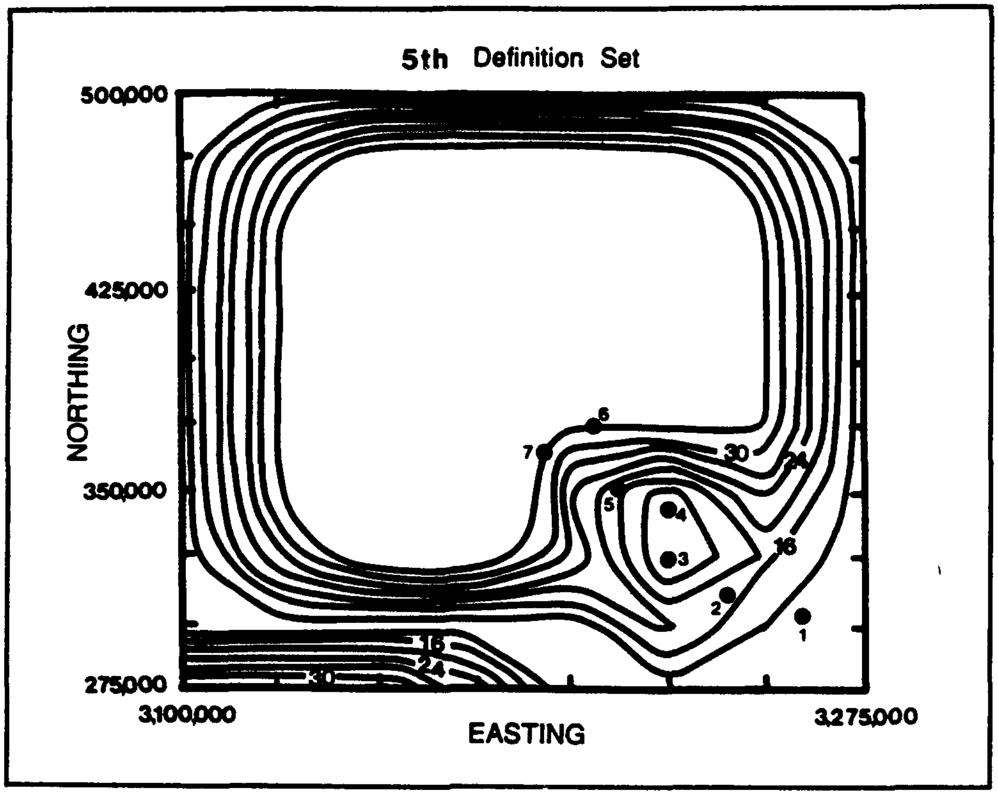
1
2
3
4
5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275,000
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EASTING
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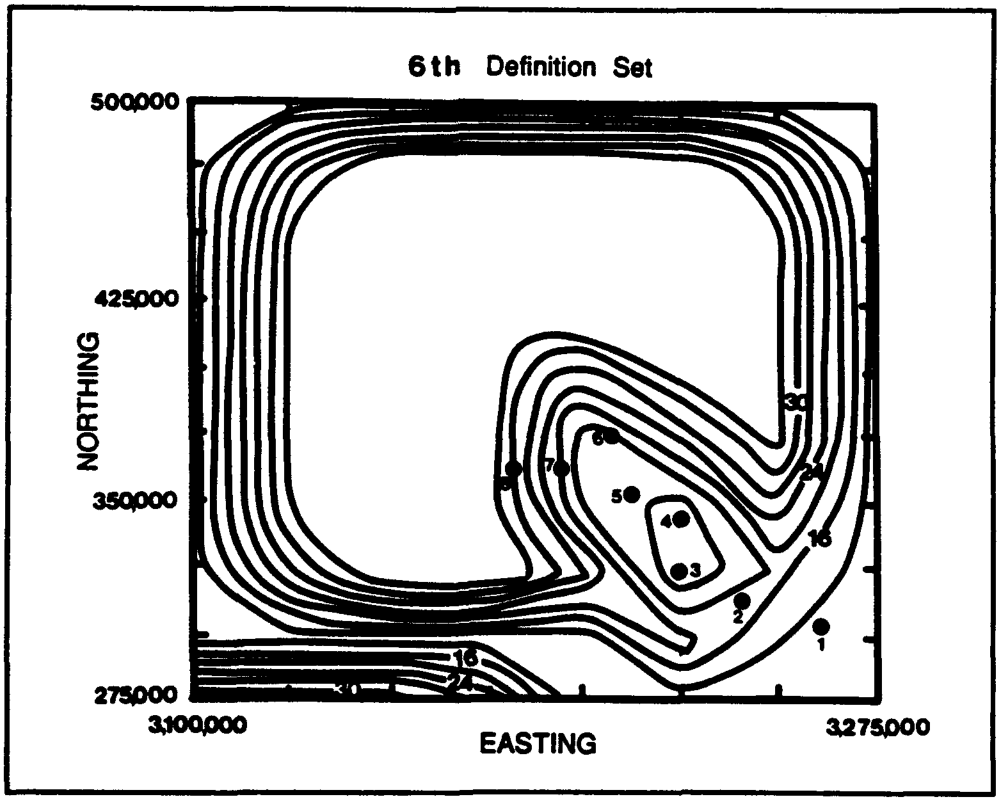
3
4
5
6
7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275,000
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EASTING
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24
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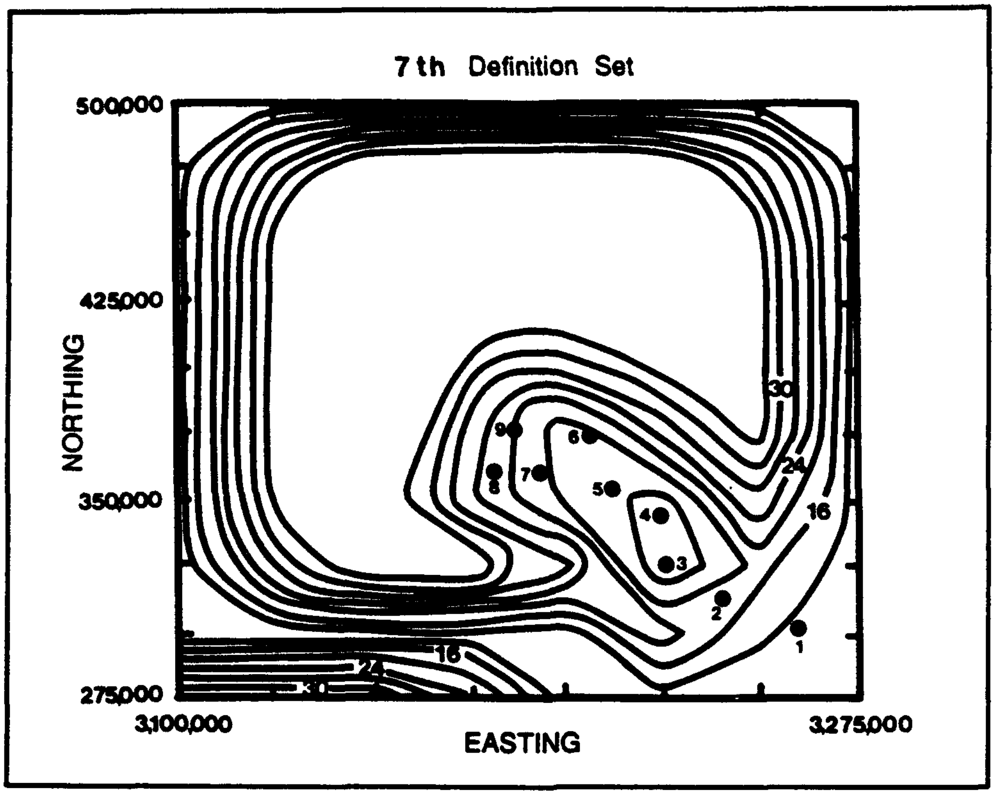
4
5
6
7
8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350,000
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3,275,000
EASTING
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24
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2
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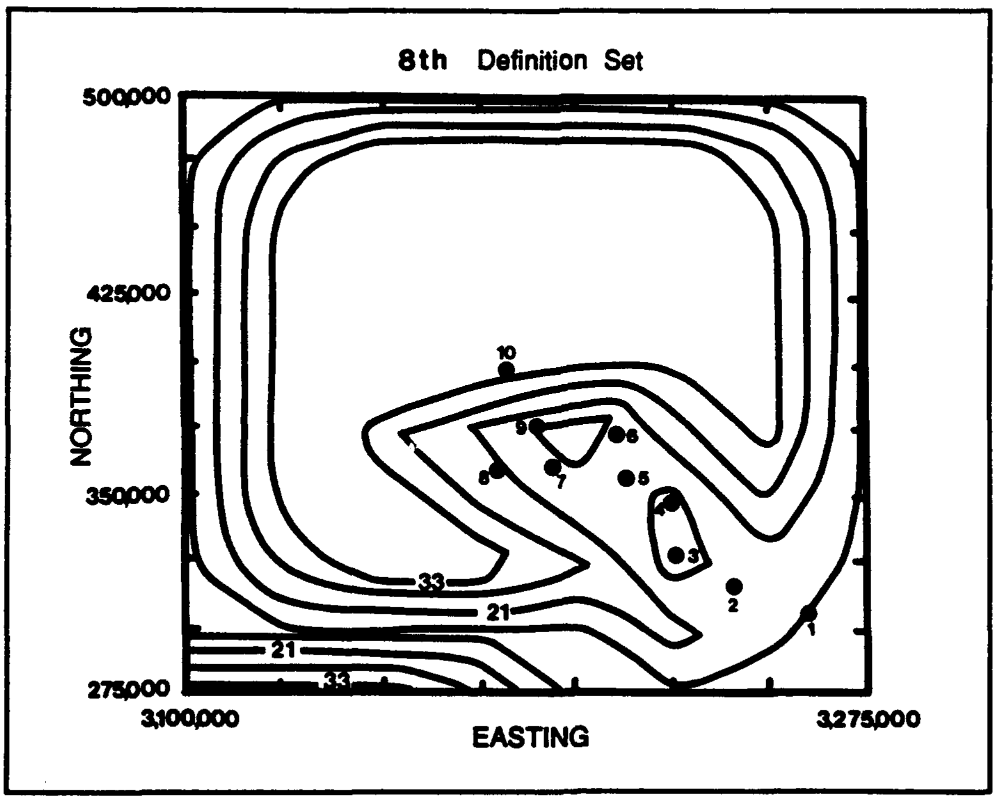
5
6
7
8
9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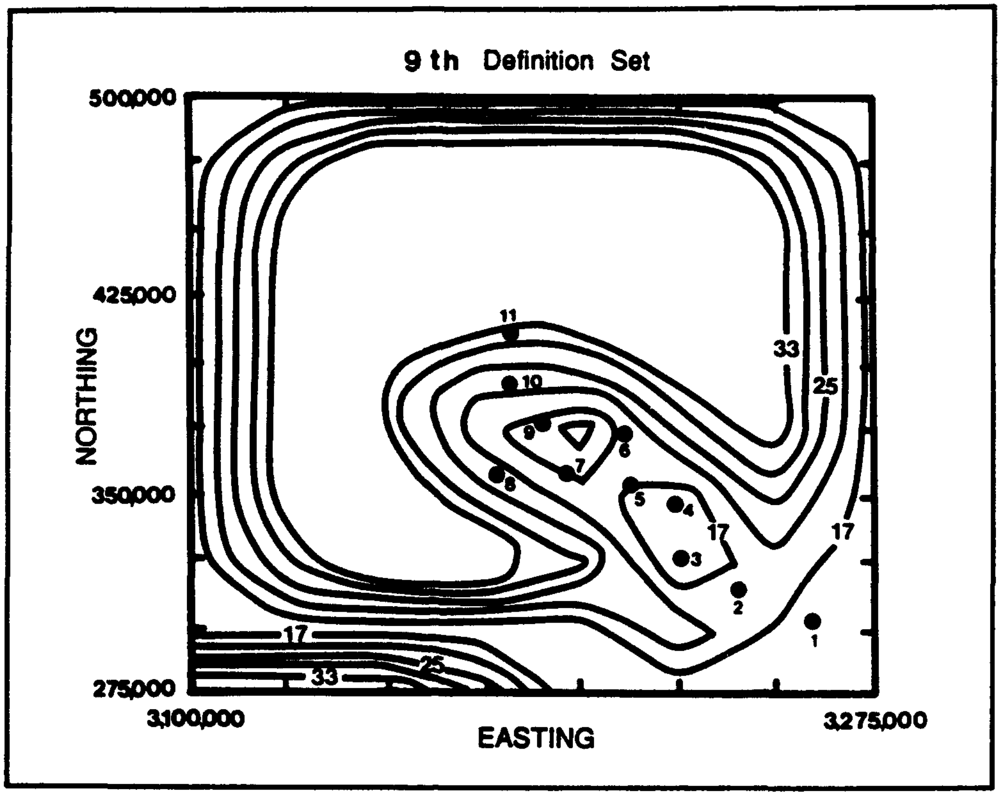
5
6
7
8
9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275,000
NORTHING
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EASTING
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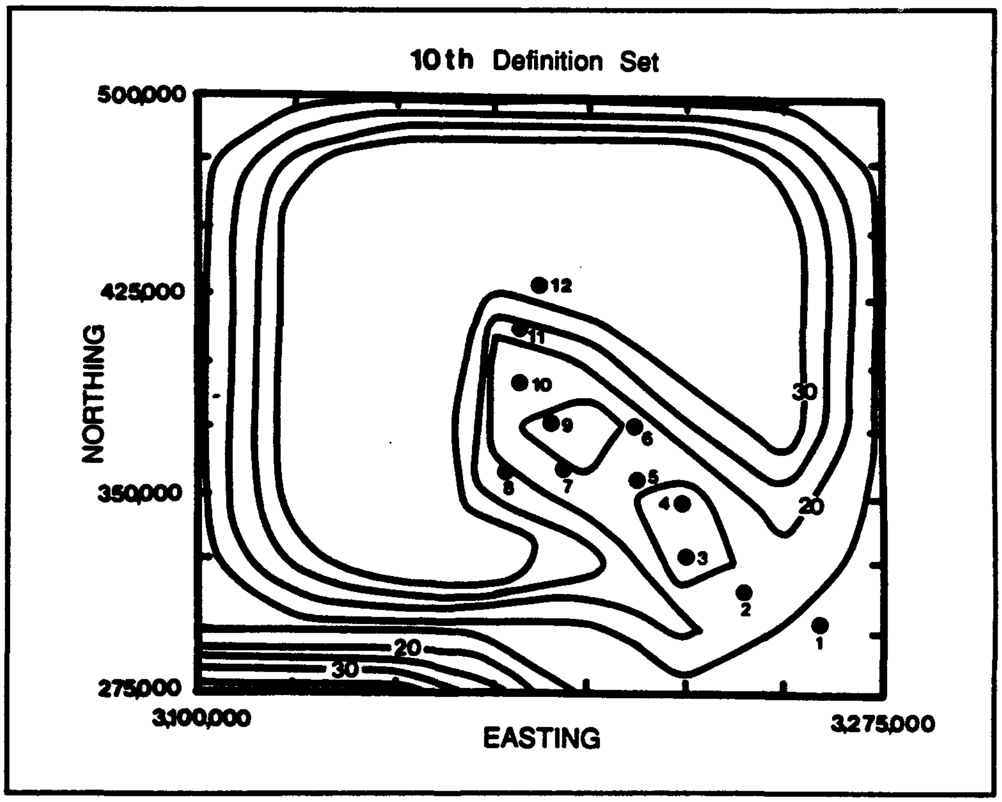
7
8
9
10
11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275,000
NORTHING
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EASTING
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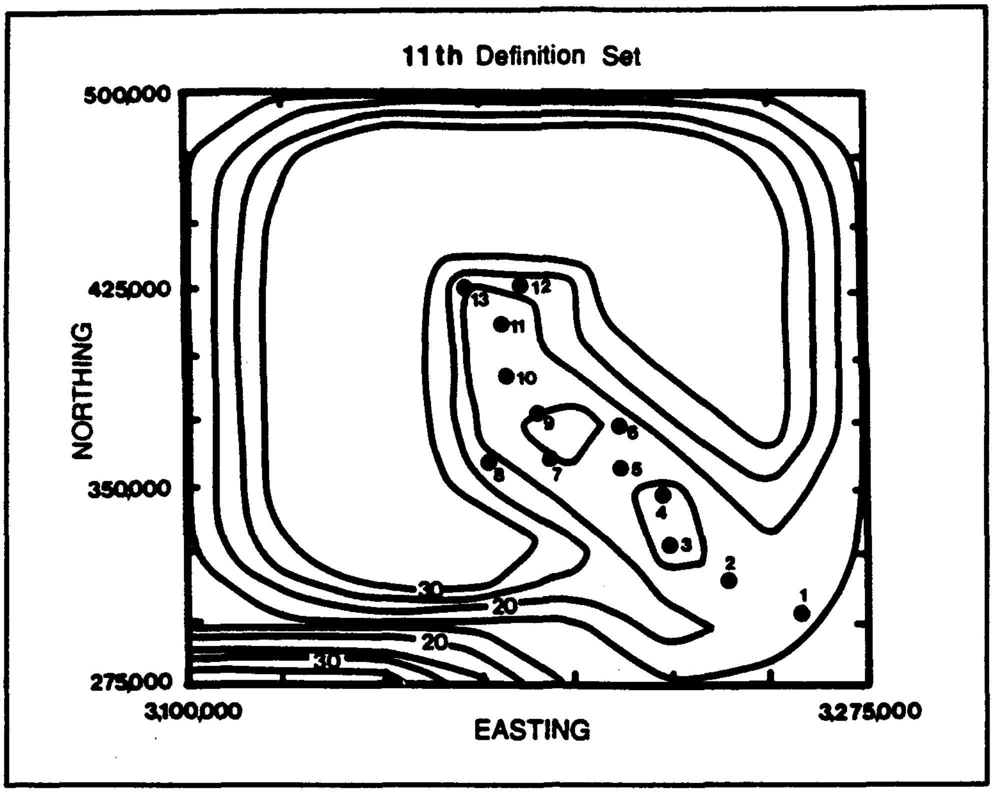
8
9
10
11
12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EASTING
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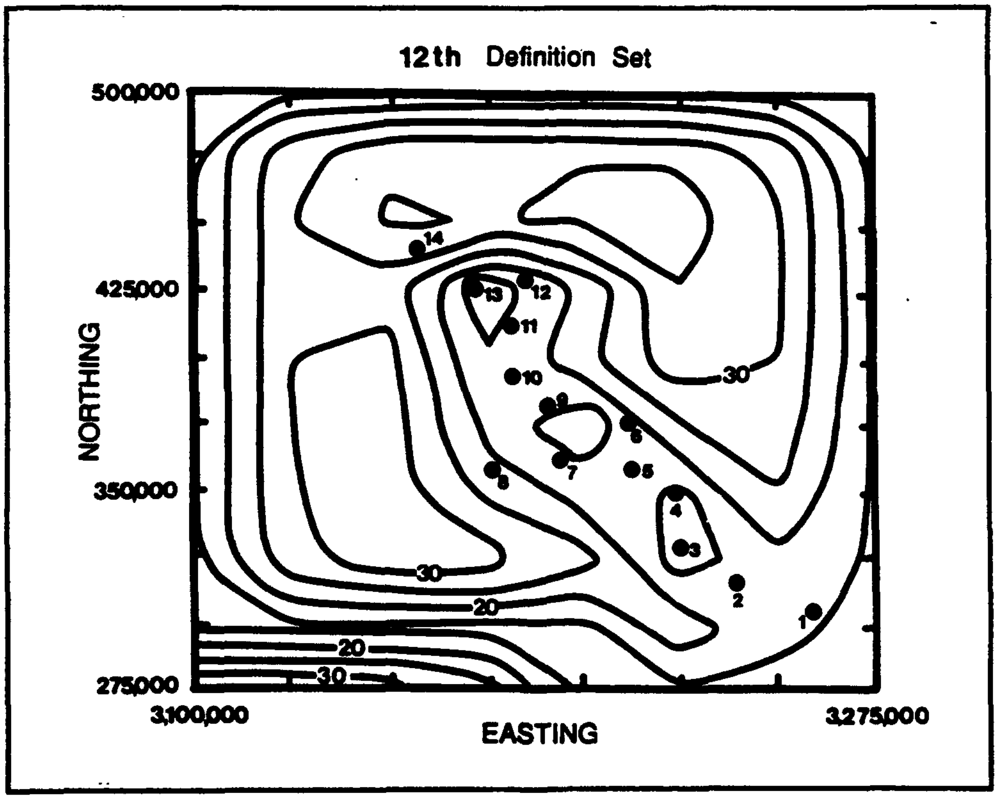
9
10
11
12
13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NORTHING
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EASTING
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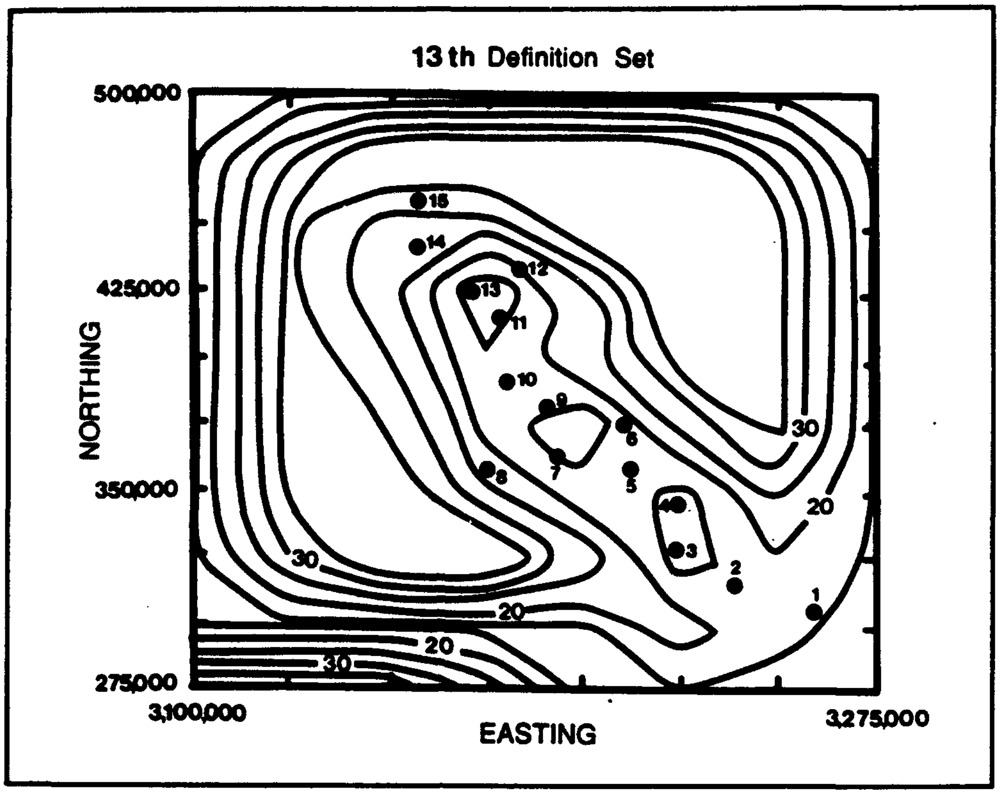
12
13
14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350,000
275,000
NORTHING
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EASTING
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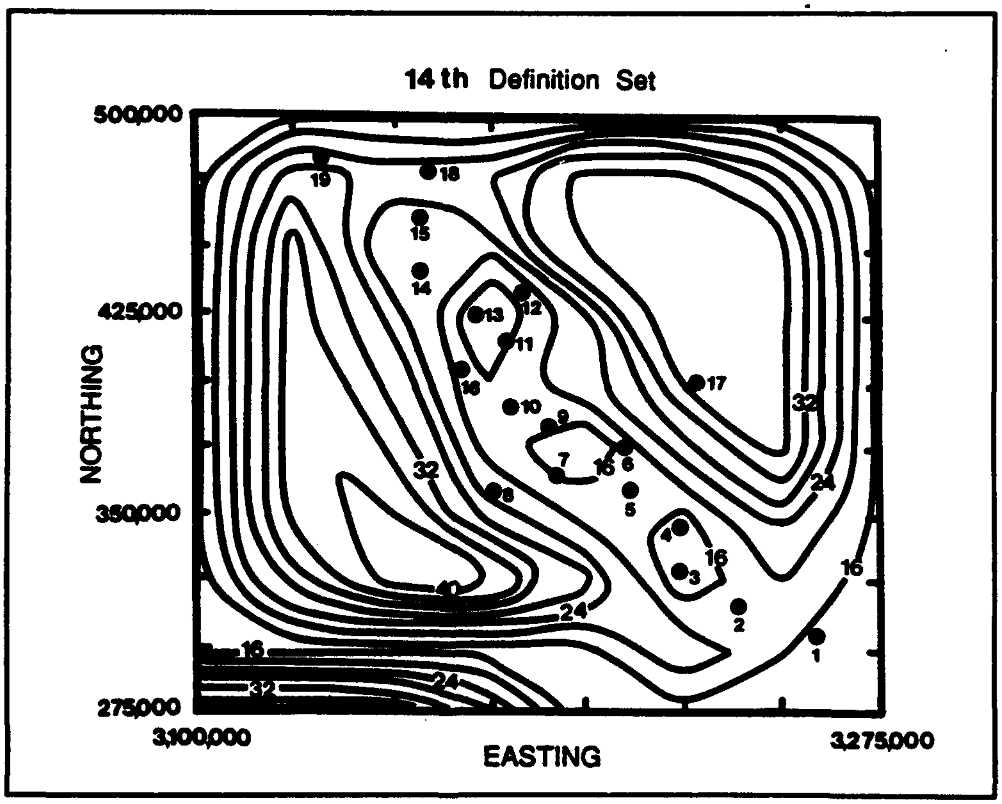
20
30
30
20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425,000
350,000
275,000
NORTHING
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3,275,000
EASTING
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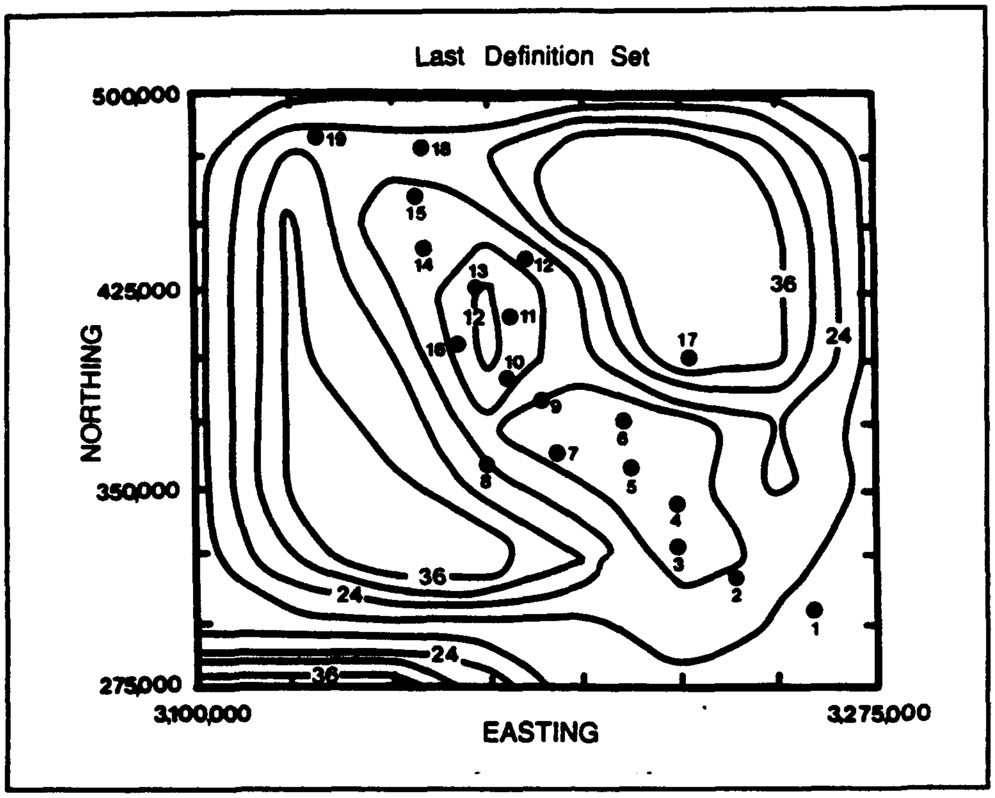
32
24
16
16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EASTING
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19
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14
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17

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13. ABSTRACT *(Maximum 200 words)*

A model was developed which uses geologically based calculations to delineate a sand body, deposited by a meandering stream, into and through a site with fewer boring locations than required by typical grid drilling. This is accomplished by establishing the environment of deposition from stratigraphic information and by assuming the sand body width is the same as the meander belt width. The meander belt width was calculated from sand thickness, once the sand body is encountered. Spacing for additional boring locations is determined from the sand body width and the probability of additional boring(s) intersecting the sand body. Once a sufficient number of borings are available, such as from site boundaries, the sand thickness is estimated for the site by the statistical method of kriging. Kriging gives the errors for the estimates. These errors are used in combination with the spacing determined from the probability of other boring(s) intersecting the sand body to select a new boring location. The additional boring location(s) are selected in areas with the most error at the determined spacing.

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